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CHARACTERISTICS OF CONIFER FOLIAGE

Final Report

by

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between

The Rocky Mountain Forest and Range Experiment Station
USDA, Forest Service
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and

The Environmental Studies Laboratory
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*This paper is dedicated to Dr. Clarence C. "Clancy" Gordon who did not live to see its completion.

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SUMMARY

The primary objectives of this study were to quantify selected baseline characteristics of ponderosa pines growing on the Custer National Forest of eastern Montana and to determine whether there have been any changes in these characteristics as of 1980, three years after coal conversion began at Colstrip, Montana, the site of two 350 MW coal-fired electrical power generating stations. Secondary objectives were to gain some understanding of the factors influencing the levels of these characteristics and determine which of these characteristics have the greatest potential to serve as indicators of air pollution.

To accomplish these goals, 20 permanent sampling sites were established in 1975 throughout the Fort Union Basin and surrounding region. Ten trees were sampled at each site and the foliage from each tree segregated and analyzed by age. The foliar concentrations of fluoride and sulfur, as well as the frequency of occurrence and amount of foliar damage due to tip burn, mottling, basal and weevil damage, and miscellaenous pathologies were determined. Average needle length and weight as well as average fascicular cross sectional area and retention were also determined.

To determine which of the characteristics studied were indeed indicators of air pollution, a pine stand located in a chronically-polluted environment was similarly examined. This site was located on Sacrifice Bluff in Billings, Montana.

Levels of fluoride and sulfur rose on the Custer National Forest from 1.5 ppm and 480 ppm, respectively, in 1975 to 3.5 ppm and 530 ppm, respectively, in 1980. The corresponding levels in Billings were 33 ppm fluoride and 1,310 ppm sulfur during the 1976 and 1980 collections. Tip burn affected 0.26% and 1.1% of the total foliar surface area in 1975 and 1980, respectively,

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on the Custer National Forest, while 3.34% of the total foliar surface area was damaged at Billings. Mottling affected 0.39% and 3% of the total foliar surface area on the Custer National Forest in 1975 and 1980, respectively, and at Billings 20.5% of the total foliar surface area was damaged. On the Custer National Forest, 4.56% and 8.6% of the total foliar surface area was damaged by some pathology in 1975 and 1980, respectively, while at Billings, 27.4% of the total surface area was damaged. In 1975 and 1980, basal pathologies occurred on 10% of the needles, while at Billings, 31% of the needles were affected. On the Custer National Forest, 89.4% and 86.7% of the needle were retained at the time of collection in 1975 and 1980, respectively, while the average needle retention was 83.5% at Billings.

None of the changes noted between 1975 and 1980 on the Custer National Forest could be unambiguously associated with the operation of the power plants, although the quantities of fluoride and sulfur released from the power plants are of the order of magnitude necessary to produce the observed increases.

Mottling and weevil damage was seen to occur on the youngest needles in 1975 to the exclusion of the older needles, indicating age selection processes were causing these injuries. Tip burn and mottling in 1980 were seen to be a function of the number of needles remaining to be damaged, and a first order differential equation was seen to fit the data. Rates of increase in the frequency of occurrence of basal damage and needle loss were seen to increase as the needles aged, indicating some physical process akin to mortality is operating. Based on comparisons of the data collected at Billings with the analogous data from the Custer National Forest, the most sensitive and specific indicators of air pollution were determined to be the foliar levels of fluoride and sulfur, and the percent of the total foliar

surface area damaged by the various needle pathologies. Basal damage and needle retention were also chosen as indicators of air pollution most useful with the older fascicles.

The negative binomial was found to fit the frequency of occurrence data for the pathologies as long as mean frequency of occurrence was small ($X < 25\%$) or large ($X > 75\%$). When the mean frequency of occurrence of the pathology neared 50%, the assumptions behind the negative binomial failed.

These facts were used to establish limits on the number of trees required to be sampled to characterize the frequency of occurrence of these pathologies as being either slight, moderate, or severe.

A statistic was developed to serve as an index of pollution stress. This index is the total foliar surface area damaged by tip burn, mottling, and miscellaneous pathologies, exclusive of weevil damage.

SELECTED BASELINE CHARACTERISTICS OF PONDEROSA PINE FOLIAGE AND A COMPARISON OF 1975 AND 1980 COLLECTIONS IN THE VICINITY OF POWER PLANTS

INTRODUCTION

Forest ecosystems are recognized as being sensitive to a wide variety of phytotoxins found in the effluent from coal-fired power plants. These pollutants, including sulfur oxides (SO_x), nitrogen oxides (NO_x), fluorides and particulates are biologically active are are capable of causing injury to pine needles as well as other biological tissues with which they come into contact. Two 350-megawatt, coal-fired electrical power generating stations have been constructed at Colstrip, Montana, and two more, each of 750 MW capacity are presently under construction. The first Colstrip unit went on-line in September, 1975, and the second in mid-1976, although these two power plants were not running at full capacities until late 1977. When operating at full capacity, these two units together burn approximately 2.4 million tons of coal per year. Stack sampling, chemical mass balances and engineering design calculations have indicated that 5,000 tons of sulfur dioxide (SO_2), 20,000 tons of nitrogen oxides, 4 tons of fluoride and 1,000 tons of particulates are released into the atmosphere each year by each of these two units.

The source of their coal is a large (10 million tons/year) strip mine located in the immediate vicinity of the power plants. These mines are a large source of particulates in the coarse size range (50 to 150 microns) and can impact the trees growing in the surrounding region. Due to the elevated release of the emissions from the power plants (via tall stacks) and the smaller particles generated by coal combustion (80% $\leq$ 0.5 microns), these facilities are expected to have a larger sphere of influence than the surrounding mines.

Public lands administered by the USDA Forest Service are located as close as 24 miles downwind (southeast) of these generating facilities. National energy policy calls for increased coal mining and conversion in this region. The increase in energy production-related activities will result in the release of large quantities of toxic materials into the surrounding environment. Since extensive stands of healthy ponderosa pines are located in the area and are known from previous scientific studies to be very susceptible to SO_2 and fluoride damage (Davis and Wilhour, 1976; Treshow and Pack, 1970), the characterization of the health of pristine ponderosa pine ecosystems is urgently required to be able to quantify any changes which may occur in the future.

The purpose of this study is fourfold: The first objective is to characterize selected pre-operational biological and physical characteristics of a pristine ponderosa pine ecosystem as found on the Custer National Forest in 1975. The second objective is to quantify any changes observed between 1975 and 1980. The third objective is to characterize the nature of the baseline distributions of selected pathologies to assist future studies of this nature by being able to determine the optimum number of study sites and samples required to assess the state of a pine forest's foliar health. The fourth objective is to compare and contrast the state of foliar health and extent of sulfur and fluoride levels in the Colstrip area with the corresponding variables found in the area known to be subject to fumigations by a coal-fired power plant burning the same type of coal as used in the Colstrip units. From these comparisons, an index of pollution stress will be developed.

MATERIALS AND METHODS

Selection of Study Sites

The Environmental Studies Laboratory has established more than 20 ponderosa pine study sites in the vicinity of Colstrip, Montana, since 1975 when the majority of the pine sites were first established. In the summer of 1975, 16 permanent sites were established in pure ponderosa pine stands located throughout the Fort Union Basin. Ten sites were located within the Ashland and Fort Howes Ranger Districts of the Custer National Forest (sites CNF 1 through CNF 10), two on private lands near Colstrip (sites CNF 12 and CNF 13), one within the Northern Cheyenne Indian Reservation (site CNF 14), one in the Bearlodge Mountains of northeastern Wyoming (site CNF 16), and two in the Black Hills of South Dakota (sites CNF 15 and CNF 17). Each site was the most elevated pine stand in the immediate area, was composed of different-aged ponderosa pines, and had a diversity of understory flora. These site locations are listed in Table 1 and are shown in Figure 1.

In 1976 three additional sites (BNW 1, BNW 2, and BNW 2) were established in the immediate vicinity of Colstrip. Although foliar pathologies were first quantified at these sites in 1976, a few trees were sampled for fluoride and sulfur in 1975. In 1978 another study site was established at Hay Coulee (site HAYCO), the location of an ambient air quality monitoring station maintained by EPA. The locations of these sites are also listed in Table 1. As can be seen from this table, the sites span a sufficiently wide range of distances from Colstrip to allow both the detection of any change in the measured foliar parameters in the Colstrip area and an estimation of the areal extent of these changes.

For comparison with these pristine sites, another site was chosen in a chronically-polluted area. Located on top of Sacrifice Bluff in Billings,

Table 1

Ponderosa Pine Study Sites

Site	Location	State	County	Section-Township-Range	Distance and Direction from Colstrip*
CNF 1	Whitetail Guard Station	Montana	Powder River	NW19 T2S R47E	34 ESE
CNF 2	Beaver Creek Divice	Montana	Powder River	SW19 T2S R46E	31 SE
CNF 3	Liscom Butte	Montana	Powder River	SE18 T1S R47E	32 ESE
CNF 4	Buckberry Creek	Montana	Powder River	SE6 T2S R48E	39 ESE
CNF 5	Home Creek Butte	Montana	Powder River	NW4 T3S R47E	37 ESE
CNF 6	Poker Jim Butte	Montana	Rosebud	SE8 T6S R44E	40 SSE
CNF 7	Indian Creek	Montana	Powder River	SW19 T7S R47E	54 SSE
CNF 8	Lyon Creek	Montana	Powder River	SE35 T6S R47E	53 SE
CNF 9	Three Mile Butte	Montana	Powder River	NW22 T4S R47E	43 SE
CNF 10	Yaeger Butte	Montana	Powder River	NW26 T4S R46E	40 SE
CNF 12	Kluver Ranch	Montana	Rosebud	SW29 T2N R42E	3 E
CNF 13	McRae Ranch	Montana	Rosebud	SW1 T1S R42E	10 SSE
CNF 14	Morningstar Viewpoint**	Montana	Rosebud	NE12 T2S R41E	16 SSE
CNF 15	Terry Peak	South Dakota	Lawrence	NE11 T50N R2E	190 SE
CNF 16	Bearlodge	Wyoming	Crook	NW16 T64N ---	150 SE
CNF 17	Crows Nest	South Dakota	Pennington	SW12 T47N R1E	190 SE
BNW 1	Board of Health Butte Gobbler Knob	Montana	Rosebud	NW12 T1N R41E	2.5 SE
BNW 2	Bailey Egan Ranch	Montana	Rosebud	NE7 T1N R42E	3.6 ESE
BNW 3	B & R Bar	Montana	Rosebud	N28 T2N R41E	1.7 NW
GB 1	Sacrifice Bluff	Montana	Yellowstone	E2 T1S R26E	90 W
HAYCO	Hay Coulee	Montana	Rosebud	NW28 T1N R42E	7 SE

*34 ESE = 34 miles east-southeast

**Northern Cheyenne Indian Reservation

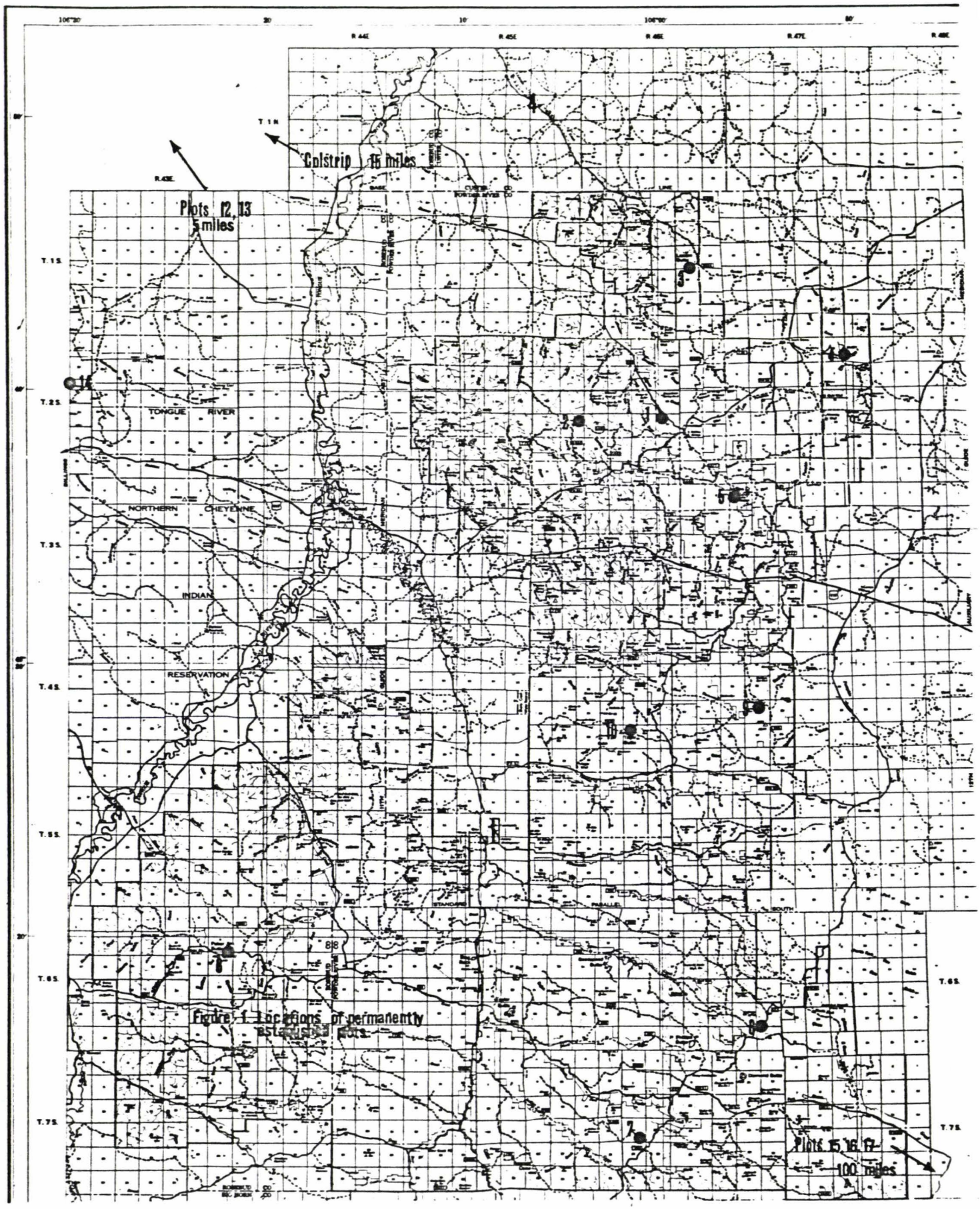

Figure 1. Ponderosa pine study sites.

Montana (Table 1), this site (GB 1) overlooks the Montana Power Company's Coreette power plant and is within 250 yards of the top of the power plant's smoke stack. Judging by the heavy coating of fine ash on the vegetation growing in the area, the site is assumed to be heavily impacted by the plume from this power plant. This facility is not the only source of polltuion in the area, as other major industrial operations are located in proximity to the site as well. By contrasting the levels of fluoride, sulfur, and the various pathologies found in Billings to the corresponding levels found in eastern Montana, some estimate can be made of the relative efficiencies of the variables studied as indicators of air pollution.

Selection of Trees

Ten ponderosa pines were selected at each site and permanently marked for future identification by attaching a metal tag in a shallow blaze at the base of the tree. Five of the trees were selected from among the "young" trees growing at the site, and five were chosen from among the "old" trees. The age categorizations were based on a tree's height and diameter. Trees were selected based on their exposure to the prevailing winds. This was determined by considering a tree's aspect, position on the slope, and height relative to the other trees growing around it.

Collection Methods

Four branches were removed from high in the crown (8 to 10 meters off the ground) of each tree on the side facing towards Colstrip, placed in individually-labeled, large plastic bags, and transported to the Environmental Studies Laboratory for analysis. While in the field, sample bags were placed in larger canvas bags and kept in the shade. Upon return to the laboratory, the bags were kept in a large walk-in cooler maintained at 40°F until ready for analysis.

Analytical Methods

Separation of Foliage Into Age Classes

Laboratory analysis began with the partitioning of the needles into age groups based on the needles' years of emergence. A given year's set of needles emerges early in the spring, and in the case of ponderosa pine, the needles are retained up to six years after emergence. To separate the foliage into age groups, the branches from a given tree were divided at the nodes to produce twig segments holding the needles from a single, specific year. The segments were kept segregated by age of foliage throughout all succeeding analyses.

Determination of Selected Growth Characteristics

The first parameter to be measured was needle retention. This is defined as the percentage of all the original needles that remained on the internode at the time of collection. Care was taken to ensure that male pine cone scars were not mistaken for missing needles. Each estimate of the needle retention for a given year's foliage on a given tree was made by averaging the needle retentions of four internodes one from each of the four branches sampled from the tree.

After needle retention was determined, all the remaining internodes were stripped of their needle fascicles and all the fascicles of like ages from a given tree were combined. Ten needle fascicles were then selected at random and their cross sectional areas were measured. The cross sectional area of a needle fascicle is defined to be the area of a circle with a radius equal to the average radius of the pine needle fascicle (usually, the fascicle is slightly elliptical in cross section and the average radius is defined to be the average of the major and minor axes of the ellipse). The area was measured

at a point where the needles emerged from the fascicular sheath. Each estimate of the cross sectional area was, therefore, the mean of ten measurements made on individual fascicles.

Next, 100 fascicles of a given age were randomly selected, the fascicular sheaths removed, and one needle selected from each fascicle (a needle fascicle normally contains two or three needles). The lengths of 25 of these needles were measured and the average needle length was calculated. Estimates of a needle's wet weight, dry weight, and percent moisture were then made. Four groups of 25 individual needles were weighed (without the fascicular sheath). The estimate of the average wet weight consisted of the mean of four groups of 25 needles each. The needles were then placed in a forced air drier at 75°C for four to five days at which time the four groups of 25 needles were reweighed and their average dry weight determined. These data were expressed as milligrams (dry weight) per individual needle. Based on the wet and dry weights of these groups of needles, the percent moisture content could be determined.

Determination of Foliar Health

Immediately after the foliage was divided into age groups and the needle retention, length and cross sectional area determined, the needles of each individual year were examined to determine the existing levels of various pathologies that are known to occur in pine needles. This was done by choosing 100 individual needles at random and examining each individually for the presence of the following pathologies. A histological description of these pathologies can be found in earlier reports (Gordon et al., 1976).

Tip burn. This is a yellowing and/or necrosis of the tip of the needle, manifested in colors of light yellow to dark brown. Occasionally, the

necrotic tissue displays a set of alternating circular bands of brown and red tissue. Since most needles have a small brown area at the tip of the needle (extending about ½ to 1 mm from the tip), the yellow area must exceed 1 mm or about 1% of the length of an average needle (135 mm) in order to be classified as tip burn. Known causes of tip burn are climatic conditions, biological agents, and atmospheric pollution.

Basal scale. Basal scale is the presence of a slit-like lesion of the epidermal and hypodermal tissue at the base of the needle (under the fascicular sheath) and is accompanied by a slight necrosis of the mesophyll tissue in the immediate area of the slit. It is also sometimes characterized by a small localized enlargement of the mesophyll tissue which causes the hypodermal and epidermal tissues of the needle to be pushed out into a blister-like lesion.

Basal necrosis. Basal necrosis is the presence of shrunken, necrotic tissue at the base of the needle, near the dwarf shoot bud. This pathology is not in association with any slit or swelling that is characteristic of basal scale.

Basal scale and necrosis combined. Since there was some concern that the basal scale and basal necrosis pathologies were merely two different phases of a single phenomenon, and errors in differentiating between these two pathologies were sometimes made, the occurrence of either basal scale or basal necrosis on a needle was therefore considered to be a separate pathology.

Mottling. Mottling is a freckling of a needle that can occur anywhere along the entire length of the needle. This symptom is caused by the yellowing of mesophyll cells located beneath the epidermal and hypodermal tissues.

Weevil damage. A needle was considered to be damaged by weevils if any parts of the needle appeared to have been chewed away. This often occurred along one margin of the needle.

Unclassified pathology. This category included miscellaneous needle injury such that it could not be considered any of the above pathologies. Wind damage was one particular type of damage that was included in this category.

Healthy needle. This indicates that a needle is free of any of the above-mentioned pathologies.

Amount of needle surface damaged by each pathology. After the frequency of occurrence of the individual pathologies was determined, the percent of the total foliar surface area of all the needles of a given age that was affected by each of the pathologies was estimated. This was accomplished by multiplying the proportion of all needles that have a given pathology by the proportion of the affected needle's surface area that was injured. For example, if 25% of all the needles was afflicted with tip burn and 25% of the surface area of the tip burned needles was injured, then 6.25% of the total surface area of all the needles was (on the average) affected by tip burn.

Total necrosis. By summing, over all pathologies, the percentages of the total foliar surface area that was injured by each of the individual pathologies, an estimate of the percentage of the total foliar surface area that was affected (by some pathology) could be determined.

RESULTS

Site Specific Data

The amount of data collected during the course of this investigation was necessarily very large. A quick glance at the number of sites established (21) and the number of variables measured at each site (20) gives some idea of the enormity of any compendium of raw data. However, as increasing levels of pollution render the existence of unpolluted control areas and opportunities for baseline studies to be relics of the past, future researchers will have a great need for site specific, historical baseline data. It is, therefore, these raw data that will serve as a historical reference point in any future studies of the long-term changes in the health of ponderosa pine ecosystems. Consequently, it was felt necessary to first present the summary statistics for each of the variables studied for each of the study sites established for the years 1975 and 1980, the years of principle focus in this report. This is done in Appendices A, B, and C.

The appendices are arranged by variable studied (fluoride, sulfur, tip burn, etc.). Under each category of pathology are arranged all the sites for which that pathology was determined. The sites are arranged in the following order: the CNF sites, followed by the BNW sites, and then HAYCO and GB 1. Appendix A is a graphical summary of each of the variables studied and presents on a single graph the results of both the 1975 and 1980 collections at a single site. Appendices B and C detail the raw data that serves as the basis of these graphs. Appendix B is a statistical summary of the 1975 data, while Appendix C is a summary of the 1980 data. As in the case of Appendix A, the data are grouped by variable studied, with the individual sites presented on individual tables. As an aide in quickly finding any desired table of raw data, a three-part code is placed at the bottom of each appendix table,

immediately above the page number. The first part of the code is the year of collection (1975 or 1980), the second part is the variable being summarized (fluoride, sulfur, tip burn, etc.), and the third part is the name of the site (CNF 1, CNF 2, BNW 1, etc.) at which the variable was observed.

The error bars indicated on all figures in both the appendices and the body of the main text are the 95% confidence limits of the mean.

Fluoride

The 1975 collection serves to define the baseline levels of fluoride in the ponderosa pine needles growing in the study area. To arrive at a forest wide average, CNF sites 1 through 14 were pooled together. The BNW sites were excluded as their proximity to the mining activites in Colstrip may result in the contamination of the needles with high levels of dust, which may cause an overestimate of the fluoride levels in the needles. The CNF sites 15, 16 and 17 were excluded due to their great distance from the main body of the study area.

Table 2 summarizes the fluoride analyses performed on the pine needles collected in 1975. As can be seen, fluoride levels change very slightly with time, the first year needles having the lowest levels of fluoride (1.21 ppm) and the fourth year needles having the highest levels (1.62 ppm). The trees sampled during the summer of 1980 have been subject to the power plant emissions for approximately three years. In the course of these three years, some 25 tons of fluoride may have been released into the environment by Colstrip Units 1 and 2.

The results of the 1980 collection are presented in Table 3. As can be seen, the fluoride levels have increased by a factor of two over what they were in 1975. The average fluoride content of the first year's needles rose to 3.02 ppm, while the oldest needles sampled in 1980 (fifth year needles) had an average fluoride concentration of 3.13 ppm.

Table 2

PARTS PER MILLION (PPM) FLUORIDE IN PINE NEEDLES
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1975 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	55	125	125	125	0
Maximum Value	3.80	4.20	4.40	5.40	-
Minimum Value	0.20	0.10	0.10	0.40	-
Average	1.21	1.42	1.42	1.62	-
Variance	0.75	0.58	0.51	0.80	-
Standard Deviation	0.87	0.76	0.71	0.89	-
Standard Error of Mean	0.12	0.07	0.06	0.08	-
Width of 95% Confidence Limit	0.23	0.13	0.13	0.16	-
Sample Precision	19.37	9.44	8.89	9.76	-
5% Quantile	0.20	0.40	0.30	0.50	-
25% Quantile	0.60	0.90	0.90	0.90	-
50% Quantile (Median)	0.90	1.30	1.40	1.50	-
75% Quantile	1.50	1.90	1.80	2.00	-
95% Quantile	3.30	2.80	2.70	3.30	-
Coefficient of Dispersion	0.62	0.40	0.36	0.49	-
Coefficient of Variation	71.62	53.30	50.19	55.12	-
Skewness	1.38	0.75	0.71	1.34	-
Standard Error	0.32	0.22	0.22	0.22	-
Width of 95% Confidence Limit	0.63	0.42	0.42	0.42	-
Probability of Occurrence (%)	0.00	0.06	0.10	0.00	-
Kurtosis	1.21	0.57	1.53	2.73	-
Standard Error	0.63	0.43	0.43	0.43	-
Width of 95% Confidence Limit	1.24	0.84	0.84	0.84	-
Probability of Occurrence (%)	5.54	18.33	0.04	0.00	-
Kolmogorov-Smirnov Maximum	0.21	0.11	0.09	0.10	-
95% K-S Critical Value	0.18	0.12	0.12	0.12	-
95% Lilliefors Critical Value	0.12	0.08	0.08	0.08	-
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	0.20	0.30	0.20	0.40	-
5% Upper	0.50	0.50	0.50	0.60	-
95% Lower	2.70	2.40	2.50	2.70	-
95% Upper	3.80	3.30	3.00	4.50	-

Table 3

PARTS PER MILLION (PPM) FLUORIDE IN PINE NEEDLES
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1980 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	70	70	69	70	69
Maximum Value	6.30	7.70	6.90	9.40	6.50
Minimum Value	0.60	0.70	0.60	0.30	0.70
Average	3.02	3.11	3.02	3.02	3.13
Variance	2.40	2.55	2.45	3.08	2.61
Standard Deviation	1.55	1.60	1.57	1.76	1.61
Standard Error of Mean	0.19	0.19	0.19	0.21	0.19
Width of 95% Confidence Limit	0.37	0.38	0.38	0.42	0.39
Sample Precision	12.23	12.23	12.46	13.87	12.38
5% Quantile	0.70	0.80	0.90	0.90	0.80
25% Quantile	1.80	2.00	1.80	1.70	1.90
50% Quantile (Median)	2.75	2.75	2.70	2.65	3.00
75% Quantile	4.30	4.20	4.00	4.30	4.10
95% Quantile	5.70	6.10	6.10	5.70	6.20
Coefficient of Dispersion	0.79	0.82	0.81	1.02	0.83
Coefficient of Variation	51.29	51.29	51.85	58.17	51.51
Skewness	0.40	0.66	0.71	0.87	0.37
Standard Error	0.29	0.29	0.29	0.29	0.29
Width of 95% Confidence Limit	0.56	0.56	0.57	0.56	0.57
Probability of Occurrence (%)	16.12	2.09	1.34	0.24	19.81
Kurtosis	-0.88	-0.08	-0.24	1.01	-0.79
Standard Error	0.57	0.57	0.57	0.57	0.57
Width of 95% Confidence Limit	1.11	1.11	1.12	1.11	1.12
Probability of Occurrence (%)	11.87	88.87	66.94	7.58	16.85
Kolmogorov-Smirnov Maximum	0.10	0.11	0.14	0.10	0.09
95% K-S Critical Value	0.16	0.16	0.16	0.16	0.16
95% Lilliefors Critical Value	0.11	0.11	0.11	0.11	0.11
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	0.60	0.70	0.60	0.30	0.70
5% Upper	1.40	1.20	1.50	1.00	1.20
95% Lower	5.40	5.50	5.50	5.30	5.40
95% Upper	6.30	7.70	6.90	9.40	6.50

The difference between the 1975 and 1980 collections can be seen in Figure 2. As shown, the fluoride levels are higher for all ages of foliage in the 1980 collections, with the first-year needles displaying the greatest increases and the oldest needles displaying the smallest increases. This is due primarily to the fluoride concentrations being a function of age in 1975 but not in 1980.

Examination of the graphical summaries of each individual site's fluoride levels listed in Appendix A discloses that no one site is responsible for this increase, but rather it appears to be a general feature of most of the sites. However, if the sites are split into two groups, one group being all those sites less than 25 km from Colstrip and the other group all those sites greater than 25 km, it is noted that the mean increase in the near sites is about twice what the mean increase for the far sites (1.76 ppm change for near sites vs. 0.88 ppm increase for far sites). There is no significant correlation between distance from Colstrip and fluoride concentration in foliage, however.

One of our objectives was to quantify the significances of any changes in the fluoride levels in the ponderosa pine foliage from 1975 to 1980. To quantify the above qualitative discussion of 1975 vis-à-vis 1980, an analysis of variance was carried out on the 1975 and 1980 data. In order to include the maximum number of sites possible (10) in the analysis, only the foliage in the second, third, and fourth years of growth were considered. The first and fifth years of foliage were ignored, as few sites had fluoride determinations performed upon these ages of foliage. The results of the ANOVA are presented in Table 4. This table indicates highly significant ($p < 0.0001$) differences between collections and sites as well as significant collection-site interactions. As suggested by the significant collection-site interaction

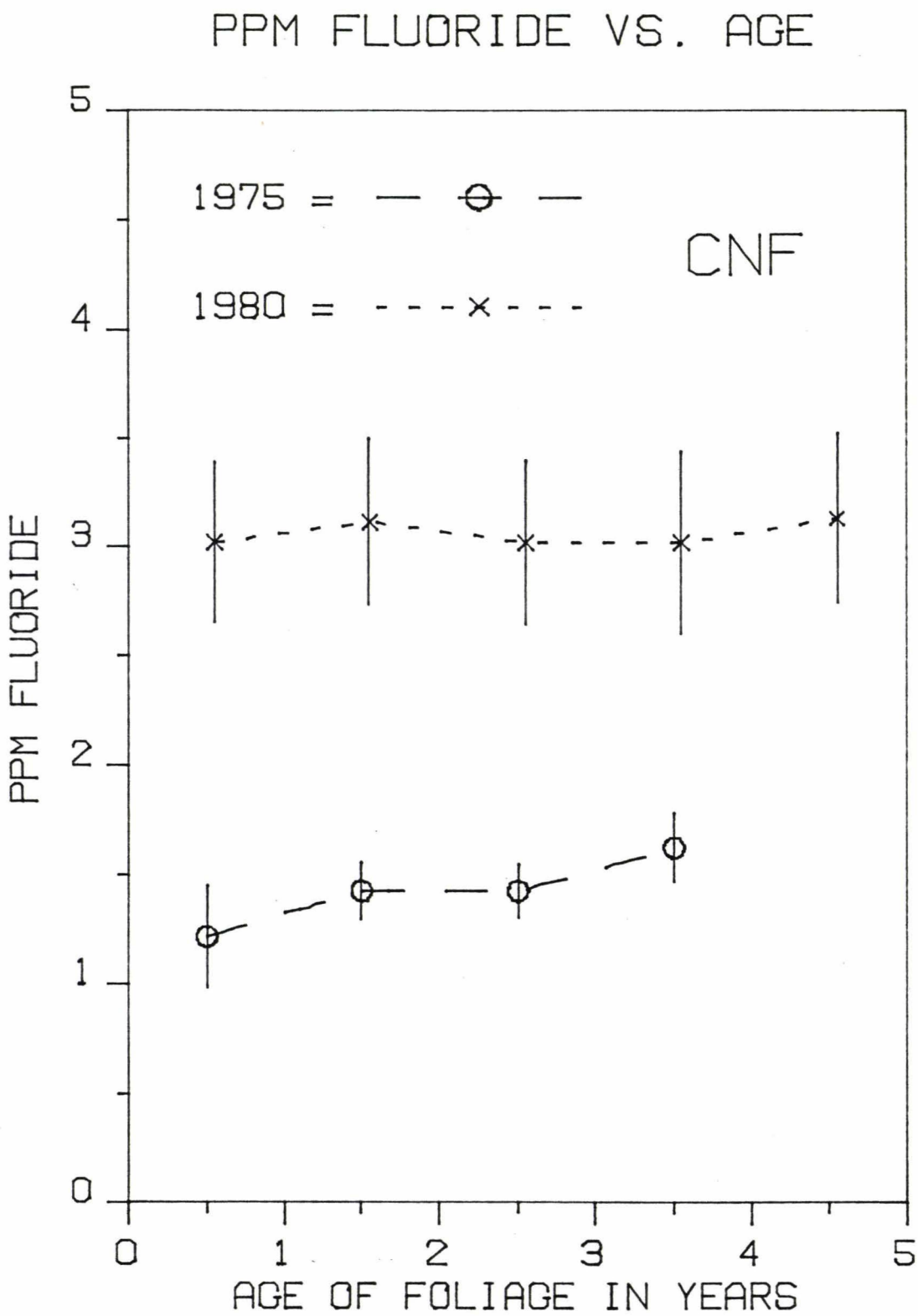

Figure 2. Comparison of fluoride levels in ponderosa pine needles at all CNF sites, 1975 and 1980 collections.

Table 4

Comparisons of Fluoride Levels in 1975 and 1980 Collections Over Custer National Forest Sites
Three-Factor ANOVA with Repeated Measures on Collection and Age of Foliage*

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Value	Probability of Occurrence
Between Trees					
Site (S)	4.614	9	0.512	4.67	<0.0001
Error	7.678	70	0.109		
Within Trees					
Collection (C)	7.415	1	7.415	147.82	<0.0001
CxS	8.064	9	0.896	17.86	<0.0001
Error	3.511	70	0.050		
Age (A)	0.157	2	0.078	2.30	0.1041
AxS	0.956	18	0.053	1.55	0.0808
Error	4.791	140	0.034		
CxA	0.199	2	0.099	3.04	0.0512
CxAxS	0.957	18	0.053	1.62	0.0630
Error	4.600	140	0.032		

*Raw data was normalized by taking the logarithms of data prior to analysis.

term, it was determined that eight sites had increased fluoride levels in 1980, while two showed no change ($p < 0.05$). There were, however, no significant ($p > 0.05$) age differences, nor age-site, collection-age, or collection-age-site interactions. These results support the observations that the primary differences between the two years of data is an overall increase in the fluoride levels in 1980 relative to 1975. This increase occurs in all examined ages of foliage to about the same extent, although there are differences among the mean levels of increase at differing sites.

Based on the observed relationships between a tree's diameter at breast height (dbh) and the weight of its foliage (Brown, 1978) and the range of the dbh's of the trees sampled in this study (25 to 50 cm), approximately 25 kg of needles (dry weight) were assumed to be on an average tree. Consequently, a 1.64 ppm increase in the fluoride content of the needles of a tree represents about 40 mg of fluoride added per tree. The relationship between dbh and the width of the tree's lower crown observed in the Brown study was utilized to estimate that an average tree subtends an area of about 25 m^2. Assuming that a tree's foliage retains about 5% of the total flux to the surface (Russell et al., 1981), then the observed levels of fluoride seen in the 1980 collections correspond to a total flux to the surface of 30 mg F/m^2.

If all the fluoride emitted from Colstrip Units 1 and 2 during a year was uniformly deposited upon all lands within 25 km of the power plants, then the flux to the surface would be 3.7 mg F/m^2, a factor one-eighth of what would be required to elevate the fluoride content of pine trees the amount observed in 1980. Consequently, some other source of fluoride must exist in the area.

One obvious source is wind blown soils. However, given the inherent uncertainties in these calculations, it is clear that there exists the

possibility that some of the added fluoride seen in the 1980 collections is due to the operation of the power plants. More detailed calculations taking into account the expected nature of the plume's behavior and appropriate depositional velocities are required to obtain a more refined estimate of the potential for fluoride accumulation due to the power plant's operation.

Sulfur

Although sulfur is emitted from the Colstrip power plants in far greater amounts than is fluoride (10,000 vs. 8 tons/year, respectively, for both generating plants combined), its usefulness as a tracer for the power plant's plume is complicated by the fact that sulfur is an essential element, found in relatively high concentrations in all cells and is readily translocated throughout a living tree.

Table 5 details the nature of the sulfur levels found at the Custer National Forest sites in 1975. It is noted that in the case of fluoride, levels rose with increasing age of needle, while in the case of sulfur, just the opposite is true--the levels decrease with increasing age of foliage. In 1975 the highest levels were found in the first year's needles (512 ppm), while the lowest values were found in the oldest needles (464 ppm). This represents a decrease of about 10%.

The 1980 collection, summarized by Table 6, also displays this decrease in sulfur levels with increasing age of foliage. This table also shows that the overall levels were higher in 1980 than they were in 1975. Figure 3 graphically depicts these two collections, and it can be seen that the absolute increase in the sulfur levels was 60 ppm and the relative increase in the sulfur levels is less than the relative increase seen in the fluoride levels. The first-year needles once again show the greatest increase.

Table 5

PARTS PER MILLION (PPM) SULFUR IN PINE NEEDLES
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1975 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	55	125	125	125	0
Maximum Value	1150.00	1050.00	1100.00	1000.00	-
Minimum Value	200.00	150.00	200.00	250.00	-
Average	511.82	506.80	479.60	464.20	-
Variance	31663.30	19519.92	16757.90	13219.11	-
Standard Deviation	177.94	139.71	129.45	114.97	-
Standard Error of Mean	23.99	12.50	11.58	10.28	-
Width of 95% Confidence Limit	48.12	24.74	22.92	20.36	-
Sample Precision	9.40	4.88	4.78	4.39	-
5% Quantile	200.00	300.00	300.00	300.00	-
25% Quantile	400.00	400.00	400.00	400.00	-
50% Quantile (Median)	500.00	500.00	500.00	450.00	-
75% Quantile	600.00	550.00	550.00	500.00	-
95% Quantile	800.00	750.00	700.00	650.00	-
Coefficient of Dispersion	61.86	38.52	34.94	28.48	-
Coefficient of Variation	34.77	27.57	26.99	24.77	-
Skewness	0.80	0.51	1.17	1.07	-
Standard Error	0.32	0.22	0.22	0.22	-
Width of 95% Confidence Limit	0.63	0.42	0.42	0.42	-
Probability of Occurrence (%)	1.28	1.83	0.00	0.00	-
Kurtosis	2.08	1.78	4.42	3.33	-
Standard Error	0.63	0.43	0.43	0.43	-
Width of 95% Confidence Limit	1.24	0.84	0.84	0.84	-
Probability of Occurrence (%)	0.10	0.00	0.00	0.00	-
Kolmogorov-Smirnov Maximum	0.14	0.13	0.13	0.14	-
95% K-S Critical Value	0.18	0.12	0.12	0.12	-
95% Lilliefors Critical Value	0.12	0.08	0.08	0.08	-
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	200.00	200.00	250.00	250.00	-
5% Upper	300.00	350.00	300.00	300.00	-
95% Lower	700.00	650.00	600.00	600.00	-
95% Upper	1150.00	900.00	950.00	800.00	-

Table 6

PARTS PER MILLION (PPM) SULFUR IN PINE NEEDLES
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1980 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	97	97	97	97	97
Maximum Value	1050.00	900.00	950.00	1000.00	900.00
Minimum Value	250.00	250.00	300.00	250.00	300.00
Average	614.95	535.57	535.05	517.01	495.36
Variance	20581.51	21820.77	17352.34	17754.51	15212.63
Standard Deviation	143.46	147.72	131.73	133.25	123.34
Standard Error of Mean	14.57	15.00	13.37	13.53	12.52
Width of 95% Confidence Limit	28.92	29.78	26.56	26.86	24.86
Sample Precision	4.70	5.56	4.96	5.20	5.02
5% Quantile	400.00	350.00	400.00	350.00	350.00
25% Quantile	550.00	400.00	450.00	450.00	400.00
50% Quantile (Median)	600.00	500.00	500.00	500.00	500.00
75% Quantile	700.00	650.00	600.00	550.00	600.00
95% Quantile	900.00	850.00	850.00	800.00	700.00
Coefficient of Dispersion	33.47	40.74	32.43	34.34	30.71
Coefficient of Variation	23.33	27.58	24.62	25.77	24.90
Skewness	0.47	0.56	0.97	1.06	0.81
Standard Error	0.24	0.24	0.24	0.24	0.24
Width of 95% Confidence Limit	0.48	0.48	0.48	0.48	0.48
Probability of Occurrence (%)	5.46	2.15	0.01	0.00	0.09
Kurtosis	0.50	-0.31	0.61	1.77	0.89
Standard Error	0.49	0.49	0.49	0.49	0.49
Width of 95% Confidence Limit	0.95	0.95	0.95	0.95	0.95
Probability of Occurrence (%)	30.40	52.96	20.82	0.03	6.61
Kolmogorov-Smirnov Maximum	0.13	0.13	0.16	0.17	0.14
95% K-S Critical Value	0.14	0.14	0.14	0.14	0.14
95% Lilliefors Critical Value	0.09	0.09	0.09	0.09	0.09
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	250.00	250.00	300.00	250.00	300.00
5% Upper	450.00	400.00	400.00	400.00	350.00
95% Lower	800.00	750.00	750.00	700.00	650.00
95% Upper	1050.00	900.00	950.00	1000.00	900.00

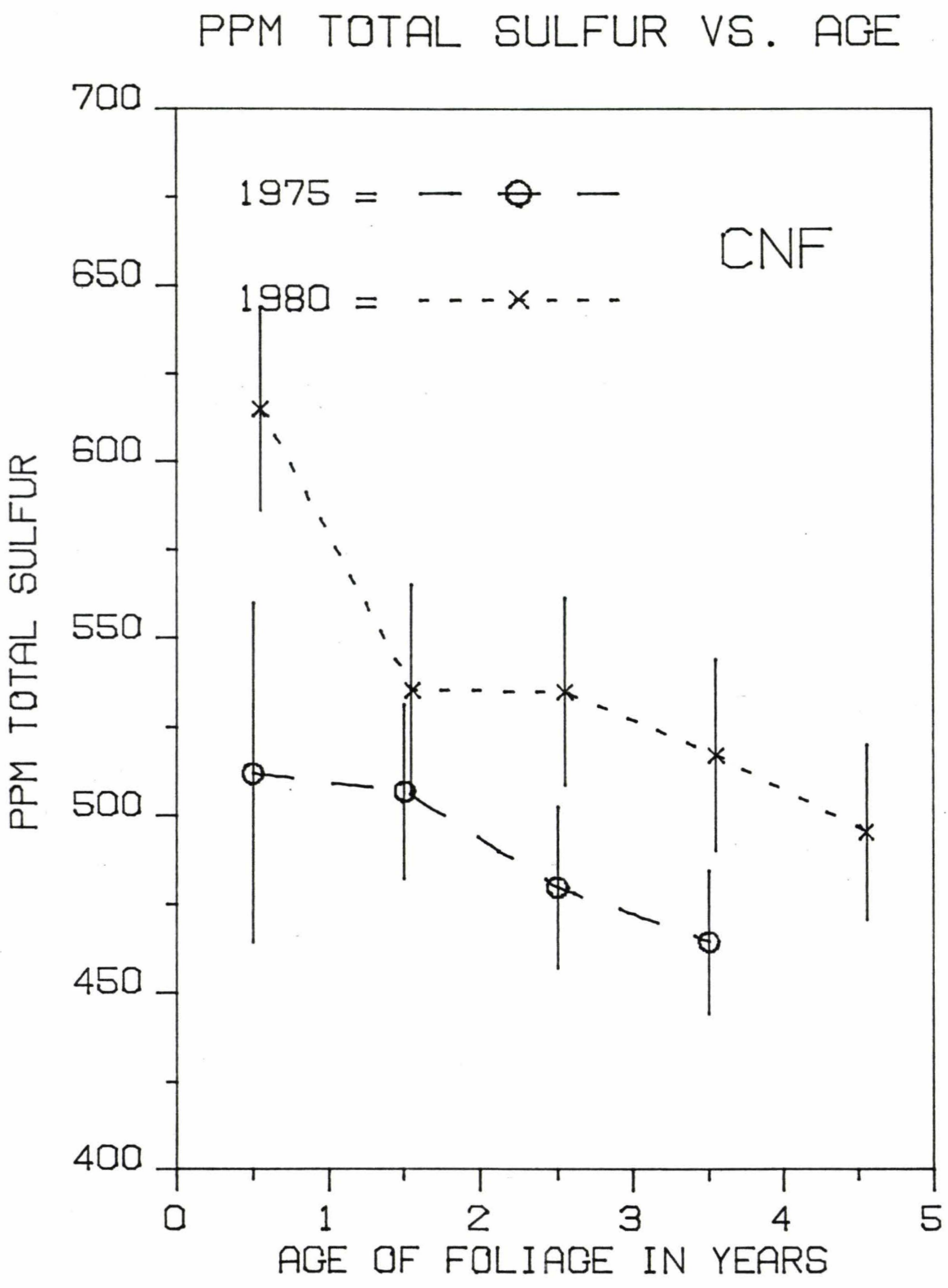

Figure 3. Comparison of sulfur levels in ponderosa pine needles at all CNF sites, 1975 and 1980 collections.

An analysis of variance was performed upon the sulfur data collected in 1975 and 1980. The results of this ANOVA are presented in Table 7. This table is very similar in its conclusions to the ANOVA table summarizing the fluoride data (Table 4). It can be seen from Table 7 that there are highly significant differences ($p < 0.001$) among sites, collections, and ages, as well as collection-site interactions (6 sites increased, 1 site declined, and 3 were unchanged), although there are no significant ($p > 0.05$) age-site or collection-age interactions.

The mean difference in the sulfur levels found in 1975 and 1980 was shown above to be 60 ppm. This corresponds to 1.5 grams of sulfur added per tree and a sulfur flux to the surface of 1.2 g/m^2 using the same type of calculations as in the section on fluoride. In one year with Colstrip Units 1 and 2 operating at full capacities, approximately 10,000 tons of sulfur may be released into the environment. Depositing all of this sulfur upon the lands within 25 km of Colstrip corresponds to a total cumulative flux to the surface of 4.6 g S/m^2. This is an amount four times greater than the 1.2 g/m^2 required to raise the sulfur level of a tree by 60 ppm. It must be remembered, however, that not all of the sulfur emitted by the power plants is deposited within 25 km. These calculations do suggest, however, that the amount of sulfur emitted is large enough to cause the observed increases in the sulfur levels if the plume regularly impacted sites in the vicinity of Colstrip (< 25 km).

Tip Burn

Table 8 summarizes the frequency of occurrence of tip burn at the CNF sites during 1975. The mean percentage of all needles that were found to have tip burn was 1.76 for needles in their second year of growth and 5.88 for needles in their fourth year of growth. Table 9 summarizes the percentages

Table 7

Comparisons of Sulfur Levels in 1975 and 1980 Collections Over Custer National Forest Sites
Three-Factor ANOVA with Repeated Measures on Collection and Age of Foliage*

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Value	Probability of Occurrence
Between Trees					
Site (S)	1.73986	12	0.14499	4.81	<0.0001
Error	2.86185	95	0.03012		
Within Trees					
Collection (C)	0.26120	1	0.26120	22.64	<0.0001
CxS	0.37893	12	0.03158	2.74	0.0032
Error	1.09608	95	0.01154		
Age (A)	0.05461	2	0.02730	6.07	0.0028
AxS	0.06123	24	0.00255	0.57	0.9489
Error	0.85453	190	0.00450		
CxA	0.01718	2	0.00859	1.71	0.1845
CxAxS	0.09259	24	0.00386	0.77	0.7758
Error	0.95692	190	0.00504		

*Raw data was normalized by taking the logarithms of data prior to analysis.

Table 8

PERCENTAGE OF NEEDLES AFFLICTED WITH TIP BURN
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1975 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	60	130	130	130	0
Maximum Value	6.00	96.00	75.00	100.00	-
Minimum Value	0.00	0.00	0.00	0.00	-
Average	0.17	1.76	3.68	5.88	-
Variance	0.65	75.81	121.24	249.46	-
Standard Deviation	0.81	8.71	11.01	15.79	-
Standard Error of Mean	0.10	0.76	0.97	1.39	-
Width of 95% Confidence Limit	0.21	1.51	1.91	2.74	-
Sample Precision	124.96	85.79	51.87	46.65	-
5% Quantile	0.00	0.00	0.00	0.00	-
25% Quantile	0.00	0.00	0.00	0.00	-
50% Quantile (Median)	0.00	0.00	0.00	0.00	-
75% Quantile	0.00	1.00	2.00	3.00	-
95% Quantile	1.00	7.00	19.00	32.00	-
Coefficient of Dispersion	3.90	43.04	32.90	42.45	-
Coefficient of Variation	483.63	494.28	298.84	268.75	-
Skewness	6.71	10.05	4.44	3.98	-
Standard Error	0.31	0.21	0.21	0.21	-
Width of 95% Confidence Limit	0.61	0.42	0.42	0.42	-
Probability of Occurrence (%)	0.00	0.00	0.00	0.00	-
Kurtosis	48.40	108.48	21.02	17.31	-
Standard Error	0.61	0.42	0.42	0.42	-
Width of 95% Confidence Limit	1.19	0.83	0.83	0.83	-
Probability of Occurrence (%)	0.00	0.00	0.00	0.00	-
Kolmogorov-Smirnov Maximum	0.50	0.41	0.36	0.35	-
95% K-S Critical Value	0.17	0.12	0.12	0.12	-
95% Lilliefors Critical Value	0.11	0.08	0.08	0.08	-
95% Confidence Limits of Selected Quantiles					
5% Lower	0.00	0.00	0.00	0.00	-
5% Upper	0.00	0.00	0.00	0.00	-
95% Lower	0.00	4.00	10.00	20.00	-
95% Upper	6.00	17.00	52.00	87.00	-

Table 9

PERCENT OF NEEDLE SURFACE DAMAGED BY TIP BURN
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1975 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	60	127	130	129	0
Maximum Value	0.30	4.80	13.13	17.50	-
Minimum Value	0.00	0.00	0.00	0.00	-
Average	0.01	0.07	0.27	0.44	-
Variance	0.00	0.19	1.62	3.15	-
Standard Deviation	0.04	0.44	1.27	1.78	-
Standard Error of Mean	0.01	0.04	0.11	0.16	-
Width of 95% Confidence Limit	0.01	0.08	0.22	0.31	-
Sample Precision	145.97	102.55	82.18	70.48	-
5% Quantile	0.00	0.00	0.00	0.00	-
25% Quantile	0.00	0.00	0.00	0.00	-
50% Quantile (Median)	0.00	0.00	0.00	0.00	-
75% Quantile	0.00	0.01	0.05	0.10	-
95% Quantile	0.03	0.25	0.95	2.15	-
Coefficient of Dispersion	0.22	2.55	6.02	7.18	-
Coefficient of Variation	564.91	583.85	473.46	404.47	-
Skewness	7.17	10.24	8.51	7.71	-
Standard Error	0.31	0.21	0.21	0.21	-
Width of 95% Confidence Limit	0.61	0.42	0.42	0.42	-
Probability of Occurrence (%)	0.00	0.00	0.00	0.00	-
Kurtosis	53.45	110.60	82.63	69.18	-
Standard Error	0.61	0.43	0.42	0.42	-
Width of 95% Confidence Limit	1.19	0.84	0.83	0.83	-
Probability of Occurrence (%)	0.00	0.00	0.00	0.00	-
Kolmogorov-Smirnov Maximum	0.49	0.42	0.41	0.39	-
95% K-S Critical Value	0.17	0.12	0.12	0.12	-
95% Lilliefors Critical Value	0.11	0.08	0.08	0.08	-
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	0.00	0.00	0.00	0.00	-
5% Upper	0.00	0.00	0.00	0.00	-
95% Lower	0.00	0.15	0.50	1.35	-
95% Upper	0.30	0.85	4.03	7.53	-

of the total foliar surface area that was affected by tip burn for each individual year of foliage. It is seen from this table that less than one tenth of one percent (0.07%) of the total foliar surface area of the second-year needles was affected by tip burn, and needles in their fourth year of growth are seen to have 0.44% of their total surface area injured.

The average frequency of occurrence of tip burn and the average percent of the total foliar surface area that was injured by tip burn can be utilized to reconstruct the average amount of necrotic tissue on a tip burned needle. The frequency of occurrence of tip burn times the percent of the surface area damaged on a tip burned needle equals the percent of the total foliar surface area that is damaged by tip burn. Consequently, the average amount of necrosis on a tip burned needle is equal to the total foliar surface area injured by tip burn divided by the frequency of occurrence of tip burn.

Tables 8 and 9 show that in 1975 the first-year needles had, on the average, 0.17% of all needles and 0.01% of the total foliar surface area damaged by tip burn. Consequently, 5.9% of the surface area of a tip burned needle was necrotic. Given that the average needle length is about 135 mm (see Tables 36 and 37), this amount of damage corresponds to about 8 mm of necrotic tissue on each tip burned needle. This value rises to about 10 mm of tip burn in the fourth year needles.

In 1980 the situation was very different. Tables 10 and 11 summarize the levels of tip burn on the foliage collected in 1980. Table 10 summarizes the frequency of occurrence of tip burn, while Table 11 summarizes the percent of the total foliar surface area that was damaged by tip burn. It can be seen from Table 10 that in 1980 the needles in their second year of growth had, on the average, 32 tip burned needles out of every 100, while 67% of the fourth-year needles were so afflicted.

Table 10

PERCENTAGE OF NEEDLES AFFLICTED WITH TIP BURN
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1980 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	0	96	96	96	96
Maximum Value	-	100.00	100.00	100.00	100.00
Minimum Value	-	0.00	0.00	0.00	1.00
Average	-	31.88	56.76	58.42	67.27
Variance	-	824.62	864.14	868.20	645.15
Standard Deviation	-	28.72	29.40	29.47	25.40
Standard Error of Mean	-	2.93	3.00	3.01	2.59
Width of 95% Confidence Limit	-	5.82	5.96	5.97	5.15
Sample Precision	-	18.26	10.50	10.22	7.65
5% Quantile	-	1.00	3.00	2.00	14.00
25% Quantile	-	6.00	37.50	37.00	51.00
50% Quantile (Median)	-	22.00	59.00	62.50	74.50
75% Quantile	-	49.50	83.00	84.00	89.00
95% Quantile	-	89.00	97.00	97.00	98.00
Coefficient of Dispersion	-	25.87	15.22	14.86	9.59
Coefficient of Variation	-	90.09	51.79	50.44	37.76
Skewness	-	0.84	-0.39	-0.55	-0.78
Standard Error	-	0.25	0.25	0.25	0.25
Width of 95% Confidence Limit	-	0.48	0.48	0.48	0.48
Probability of Occurrence (%)	-	0.06	11.18	2.52	0.16
Kurtosis	-	-0.44	-0.92	-0.85	-0.34
Standard Error	-	0.49	0.49	0.49	0.49
Width of 95% Confidence Limit	-	0.96	0.96	0.96	0.96
Probability of Occurrence (%)	-	37.04	5.89	8.07	48.42
Kolmogorov-Smirnov Maximum	-	0.16	0.09	0.10	0.12
95% K-S Critical Value	-	0.14	0.14	0.14	0.14
95% Lilliefors Critical Value	-	0.09	0.09	0.09	0.09
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	-	0.00	0.00	0.00	1.00
5% Upper	-	3.00	9.00	8.00	26.00
95% Lower	-	82.00	94.00	92.00	94.00
95% Upper	-	100.00	100.00	100.00	100.00

Table 11

PERCENTAGE OF NEEDLE SURFACE THAT IS DAMAGED BY TIP BURN
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1980 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	0	97	97	97	97
Maximum Value	-	4.55	12.25	17.15	17.33
Minimum Value	-	0.00	0.00	0.00	0.05
Average	-	0.33	1.23	1.75	3.29
Variance	-	0.47	3.56	8.27	13.30
Standard Deviation	-	0.69	1.89	2.88	3.65
Standard Error of Mean	-	0.07	0.19	0.29	0.37
Width of 95% Confidence Limit	-	0.14	0.38	0.58	0.74
Sample Precision	-	41.64	30.83	33.05	22.36
5% Quantile	-	0.01	0.02	0.03	0.20
25% Quantile	-	0.04	0.24	0.27	0.44
50% Quantile (Median)	-	0.15	0.36	0.41	2.95
75% Quantile	-	0.30	1.60	2.55	4.40
95% Quantile	-	1.75	4.75	4.55	14.00
Coefficient of Dispersion	-	1.42	2.89	4.71	4.04
Coefficient of Variation	-	206.56	152.94	163.92	110.91
Skewness	-	4.63	2.76	3.57	2.45
Standard Error	-	0.24	0.24	0.24	0.24
Width of 95% Confidence Limit	-	0.48	0.48	0.48	0.48
Probability of Occurrence (%)	-	0.00	0.00	0.00	0.00
Kurtosis	-	23.66	11.15	15.96	6.97
Standard Error	-	0.49	0.49	0.49	0.49
Width of 95% Confidence Limit	-	0.95	0.95	0.95	0.95
Probability of Occurrence (%)	-	0.00	0.00	0.00	0.00
Kolmogorov-Smirnov Maximum	-	0.32	0.35	0.27	0.24
95% K-S Critical Value	-	0.14	0.14	0.14	0.14
95% Lilliefors Critical Value	-	0.09	0.09	0.09	0.09
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	-	0.00	0.00	0.00	0.05
5% Upper	-	0.02	0.08	0.12	0.30
95% Lower	-	0.50	4.30	4.30	5.00
95% Upper	-	4.55	12.25	17.15	17.33

Table 11 shows that the fraction of the total foliar surface area that was necrotic due to tip burn was 0.3% for the second-year needles and 3.3% for the fifth-year needles. Based on these data, one can conclude that the pine trees had a larger percentage of their needle tips damaged in 1980 relative to 1975; they also have a larger percentage of their total foliar surface area damaged by tip burn, as shown in Figure 4.

The increase in the frequency of occurrence of tip burn is greater than the increase in the necrotic tissue, and consequently the average length of the necrotic zone associated with tip burn fell from the 8 mm recorded in 1975 for needles in their second year of growth to 1.4 mm in 1980. In the case of four-year needles, the average length of the necrotic zone fell from the 10 mm seen in 1975 to 6.6 mm in 1980.

Figure 5 summarizes the frequency of occurrence of tip burn in both 1975 and 1980. A few salient points can be drawn from this figure. The first point of interest is the higher overall frequency of occurrence of tip burn in 1980. The second point is that the proportion of needles with tip burn rises faster with age in 1980 than in 1975. These two facts suggest the presence of a phenomenon that has been operating over the entire lifetime of the needles, i.e., whatever is causing the needles to become tip burned in 1980 seems to be the result of a continuous process rather than the consequence of a unique event. If a single event occurred that could produce tip burn, then all the ages of needles should have about the same level of tip burn, assuming that the phenomenon does not damage the various-aged needles to varying extents.

Examination of the rate of increase of tip burn with age can also reveal some information as to the nature of the mechanism causing the tip burn. If the probability of a needle becoming tip burned in any year is given by k,

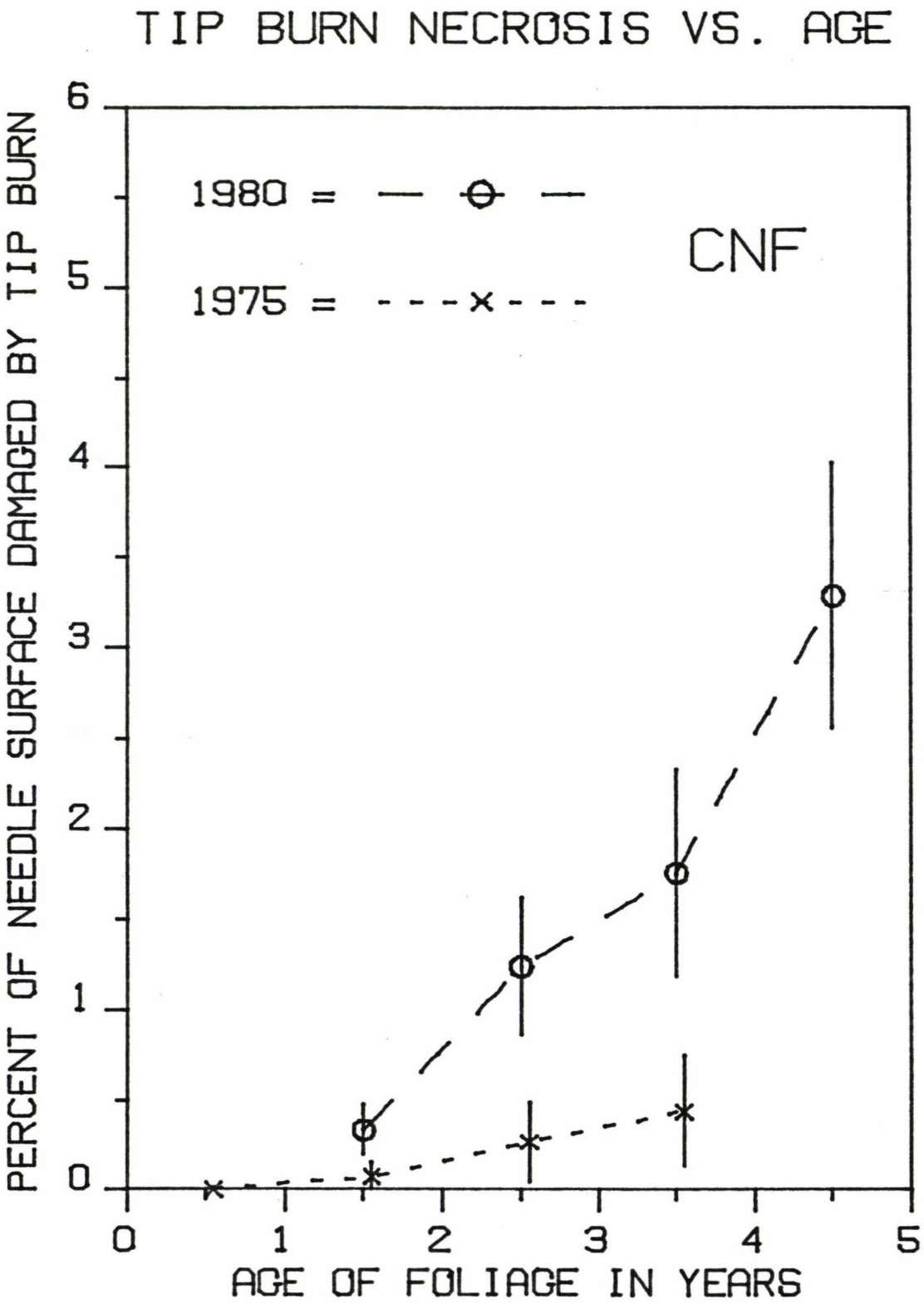

Figure 4. Percent of ponderosa pine needle surface damaged by tip burn at all CNF sites, 1975 and 1980 collections.

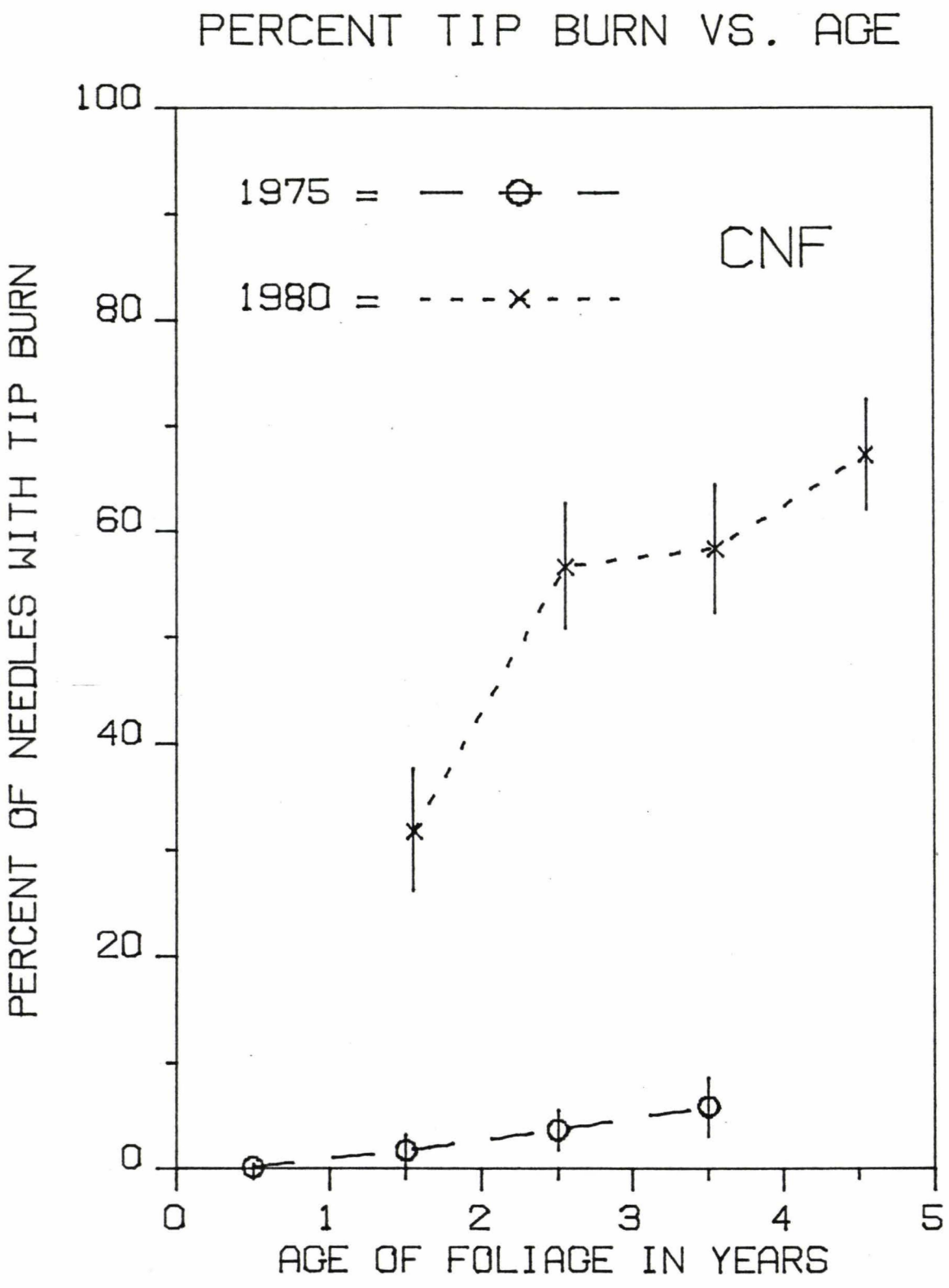

Figure 5. Percentage of ponderosa pine needles afflicted with tip burn at all CNF sites, 1975 and 1980 collections.

then the rate of transformation of non-tip burned needles into tip burned needles should follow the exponential decay law. This can be stated as:

non-tip burned needles at time t =

non-tip burned needles originally * exp (-kt)

Since all the needles are healthy at the time of emergence, the proportion of healthy needles originally is 1.0. This decay law can also be described as a first order reaction because the rate of appearance of tip burned needles is proportional to the number of non-tip burned needles in the population at any given time. This can be stated as:

d(non-tip burned needles)/dt =

-k * no. of non-tip burned needles at time t, i.e.,

$$\frac{dn}{dt} = -k * n$$

where n = no. of non-tip burned needles

A logarithmic plot of the percent of needles without tip burn versus time should be a straight line with a slope equal to -k. Figure 6 is such a graph. As can be seen, in 1975 there was a slow conversion of healthy needles into tip burned needles occurring with a rate constant (k) of 0.0196 corresponding to a half-life of 35 years. This rate constant increased to 0.22381 (corresponding to a half-life of 3.1 years) in the 1980 collections. This figure supports the theory that the rate of appearance of tip burned needles can be described as a first order phenomenon, with the probability of any particular needle becoming tip burned during any given time period remaining a constant over the life of the needle. This figure also demonstrates that the levels of tip burn were higher in 1980 than they were 1975. The reasonableness of these conclusions is suggested by the fact that the proportion of healthy needles at the time of emergence (t_o) is not significantly different ($p > .05$, $p > .5$ for 1975 and 1980 collections, respectively) from 1.0.

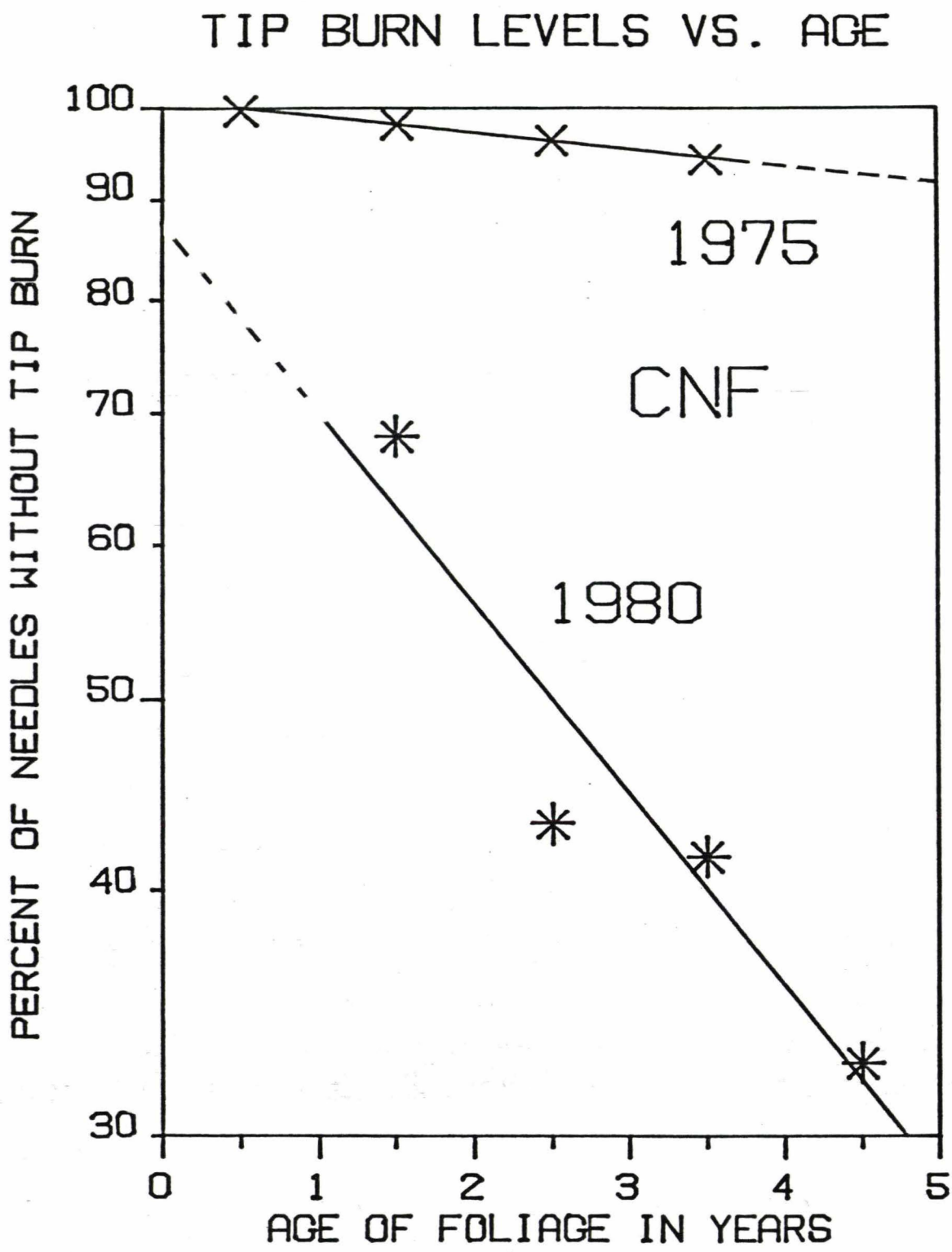

Figure 6. Levels of tip burn in ponderosa pine needles at all CNF sites, 1975 and 1980 collections.

Mottling

The patterns of mottling seen on the Custer National Forest in 1975 are different, both qualitatively and quantitatively from the patterns recorded in 1980. As seen in Table 12, the proportion of needles with mottling in 1975 was 1.2 per thousand for needles in their first year of growth, and 6.5% for needles in their fourth year of growth. The greatest changes in the frequency of occurrence of mottling is seen to occur between the first and second years of growth, with the frequency of occurrence of mottling remaining relatively constant during the second, third, and fourth years of growth.

Turning to Table 13, which summarizes the analogous data collected in 1980, it can be seen that a large increase has occurred in the percentage of needles that are mottled. In 1980 more than 50% of the needles were mottled by their second year of growth, and more than 80% were mottled by the fifth year of growth. The frequency of occurrence of mottling is also seen to increase every year, whereas in the 1975 collections, the frequency of occurrence leveled off after the second year of growth.

Figure 7 contrasts the 1975 and 1980 mottling data, demonstrating that the 1975 levels of mottling rose during the first year of growth and then leveled off. The tendency is for the younger needles to become mottled at a faster rate than the older needles. Reference to Figure 7 also shows that in 1980 a continual increase in mottling occurs in each age group. This indicates that a continuous, non-age selective mechanism is at work; i.e., the needles are being mottled without regard to age, and the mottling is occurring every year.

These differences in the levels and patterns of mottling between the 1975 and 1980 collections are reflected in the proportion of the total foliar surface area that is damaged by mottling. Table 14 summarizes the percentages

Table 12

PERCENTAGE OF NEEDLES AFFLICTED WITH MOTTLING
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1975 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	60	130	130	130	0
Maximum Value	4.00	55.00	63.00	58.00	-
Minimum Value	0.00	0.00	0.00	0.00	-
Average	0.12	5.87	7.08	6.50	-
Variance	0.34	122.97	156.89	108.42	-
Standard Deviation	0.58	11.09	12.53	10.41	-
Standard Error of Mean	0.08	0.97	1.10	0.91	-
Width of 95% Confidence Limit	0.15	1.92	2.17	1.81	-
Sample Precision	129.54	32.79	30.72	27.80	-
5% Quantile	0.00	0.00	0.00	0.00	-
25% Quantile	0.00	0.00	0.00	0.00	-
50% Quantile (Median)	0.00	0.00	1.00	2.00	-
75% Quantile	0.00	6.00	8.00	9.00	-
95% Quantile	0.50	30.00	35.00	27.00	-
Coefficient of Dispersion	2.93	20.95	22.17	16.68	-
Coefficient of Variation	501.33	188.94	176.99	160.19	-
Skewness	5.77	2.44	2.46	2.48	-
Standard Error	0.31	0.21	0.21	0.21	-
Width of 95% Confidence Limit	0.61	0.42	0.42	0.42	-
Probability of Occurrence (%)	0.00	0.00	0.00	0.00	-
Kurtosis	35.42	5.86	6.04	7.14	-
Standard Error	0.61	0.42	0.42	0.42	-
Width of 95% Confidence Limit	1.19	0.83	0.83	0.83	-
Probability of Occurrence (%)	0.00	0.00	0.00	0.00	-
Kolmogorov-Smirnov Maximum	0.53	0.30	0.28	0.26	-
95% K-S Critical Value	0.17	0.12	0.12	0.12	-
95% Lilliefors Critical Value	0.11	0.08	0.08	0.08	-
95% Confidence Limits of Selected Quantiles					
5% Lower	0.00	0.00	0.00	0.00	-
5% Upper	0.00	0.00	0.00	0.00	-
95% Lower	0.00	24.00	28.00	21.00	-
95% Upper	4.00	48.00	56.00	50.00	-

Table 13

PERCENTAGE OF NEEDLES AFFLICTED WITH MOTTLING
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1980 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	0	96	96	96	96
Maximum Value	-	100.00	100.00	100.00	100.00
Minimum Value	-	3.00	4.00	4.00	31.00
Average	-	56.50	67.78	79.05	85.41
Variance	-	934.53	840.26	552.22	337.28
Standard Deviation	-	30.57	28.99	23.50	18.37
Standard Error of Mean	-	3.12	2.96	2.40	1.87
Width of 95% Confidence Limit	-	6.20	5.87	4.76	3.72
Sample Precision	-	10.97	8.67	6.02	4.36
5% Quantile	-	9.00	19.00	32.00	44.00
25% Quantile	-	26.50	41.50	65.50	77.00
50% Quantile (Median)	-	62.00	73.50	87.00	95.00
75% Quantile	-	84.50	94.50	99.00	99.00
95% Quantile	-	100.00	100.00	100.00	100.00
Coefficient of Dispersion	-	16.54	12.40	6.99	3.95
Coefficient of Variation	-	54.11	42.77	29.73	21.50
Skewness	-	-0.09	-0.50	-1.09	-1.34
Standard Error	-	0.25	0.25	0.25	0.25
Width of 95% Confidence Limit	-	0.48	0.48	0.48	0.48
Probability of Occurrence (%)	-	72.42	4.11	0.00	0.00
Kurtosis	-	-1.36	-1.10	0.24	0.78
Standard Error	-	0.49	0.49	0.49	0.49
Width of 95% Confidence Limit	-	0.96	0.96	0.96	0.96
Probability of Occurrence (%)	-	0.54	2.38	62.05	11.13
Kolmogorov-Smirnov Maximum	-	0.11	0.14	0.19	0.24
95% K-S Critical Value	-	0.14	0.14	0.14	0.14
95% Lilliefors Critical Value	-	0.09	0.09	0.09	0.09
95% Confidence Limits of Selected Quantiles					
5% Lower	-	3.00	4.00	4.00	31.00
5% Upper	-	14.00	25.00	39.00	49.00
95% Lower	-	99.00	100.00	100.00	100.00
95% Upper	-	100.00	100.00	100.00	100.00

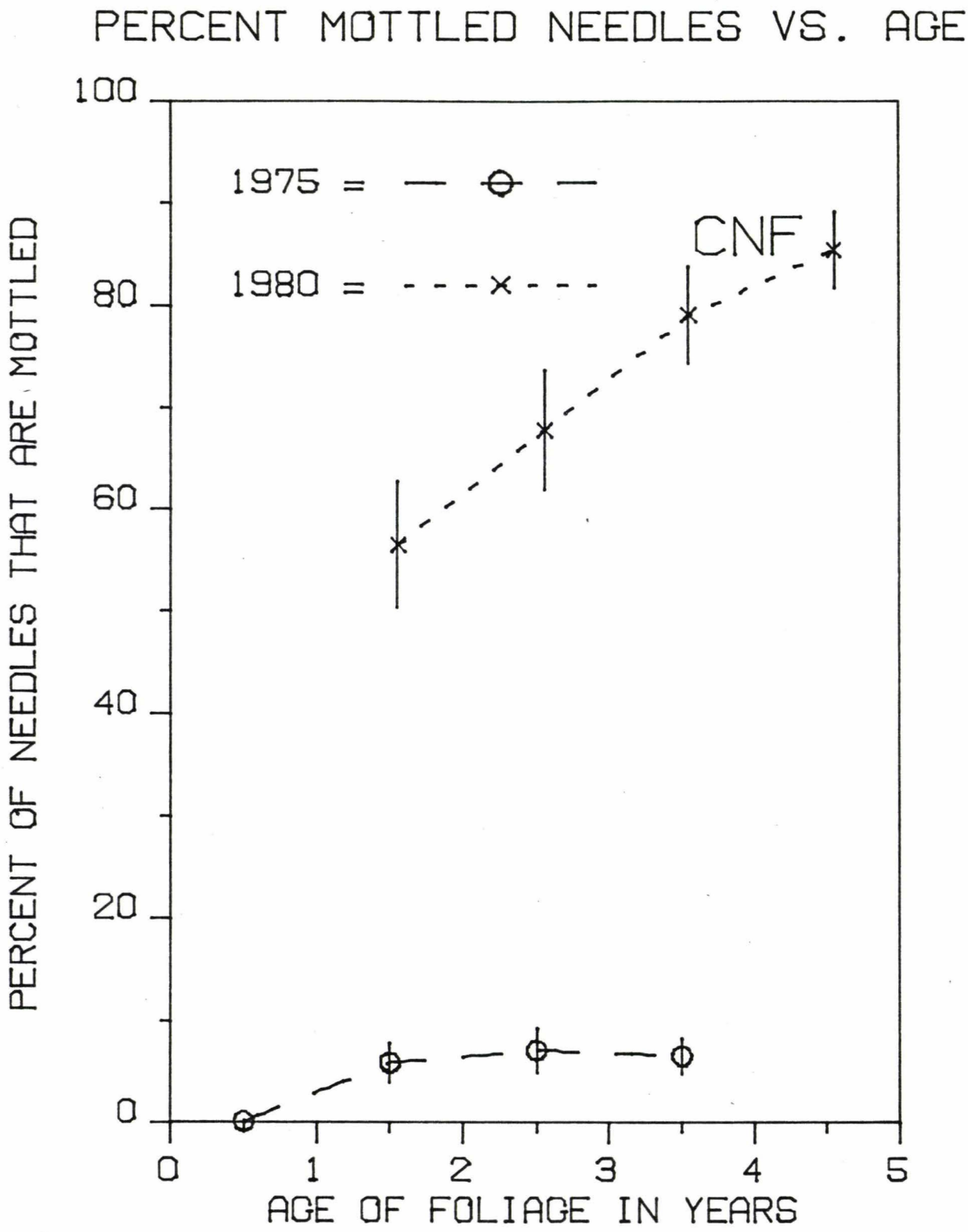

Figure 7. Percentage of needles afflicted with mottling at all CNF sites, 1975 and 1980 collections.

Table 14

PERCENT OF NEEDLE SURFACE DAMAGED BY MOTTLING
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1975 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	60	106	110	110	0
Maximum Value	0.02	8.23	6.00	8.75	-
Minimum Value	0.00	0.00	0.00	0.00	-
Average	0.00	0.34	0.45	0.39	-
Variance	0.00	1.26	1.16	1.14	-
Standard Deviation	0.00	1.12	1.08	1.07	-
Standard Error of Mean	0.00	0.11	0.10	0.10	-
Width of 95% Confidence Limit	0.00	0.22	0.20	0.20	-
Sample Precision	120.82	62.97	44.87	52.24	-
5% Quantile	0.00	0.00	0.00	0.00	-
25% Quantile	0.00	0.00	0.00	0.00	-
50% Quantile (Median)	0.00	0.00	0.01	0.02	-
75% Quantile	0.00	0.14	0.30	0.30	-
95% Quantile	0.01	1.50	2.80	1.80	-
Coefficient of Dispersion	0.01	3.67	2.56	2.96	-
Coefficient of Variation	467.59	326.89	237.40	276.36	-
Skewness	5.11	5.66	3.40	5.72	-
Standard Error	0.31	0.23	0.23	0.23	-
Width of 95% Confidence Limit	0.61	0.46	0.45	0.45	-
Probability of Occurrence (%)	0.00	0.00	0.00	0.00	-
Kurtosis	27.62	35.40	12.48	39.05	-
Standard Error	0.61	0.47	0.46	0.46	-
Width of 95% Confidence Limit	1.19	0.91	0.90	0.90	-
Probability of Occurrence (%)	0.00	0.00	0.00	0.00	-
Kolmogorov-Smirnov Maximum	0.53	0.37	0.33	0.35	-
95% K-S Critical Value	0.17	0.13	0.13	0.13	-
95% Lilliefors Critical Value	0.11	0.09	0.08	0.08	-
95% Confidence Limits of Selected Quantiles					
5% Lower	0.00	0.00	0.00	0.00	-
5% Upper	0.00	0.00	0.00	0.00	-
95% Lower	0.00	1.00	1.75	1.20	-
95% Upper	0.02	8.23	5.25	5.63	-

of the total foliar surface area that was damaged by mottling in 1975. Just as the number of mottled needles rises until the second year of growth and then levels off (Table 12 and Figure 7), so too the percent of the total foliar surface area that is damaged by mottling rises until the second year and then levels off to about 0.4% during the second, third, and fourth years of foliar growth. Given that about 6.5% of the second, third, and fourth year needles were mottled in 1975, then the 0.4% of the total foliar surface area damaged by mottling means that, on the average, about 6% of the surface area of an individual, mottled needle is damaged by mottling.

Table 15 summarizes the amount of needle necrosis due to mottling seen in 1980 collections. The percent of the total foliar surface area damaged by mottling is seen in this table to be 1.8% for the needles in their second year of growth and rises each year until it reaches 6.3% of the total foliar surface area for the needles during their fifth year of growth. The comparable data collected in 1975 indicated a relatively constant proportion of 0.4% of the surface area was damaged.

Figure 8 graphically portrays these data and demonstrates the differences in the patterns of total foliar surface area damaged by mottling. These data imply that, in 1980, mottled needles in their second year of growth had, on the average, 3% of their surface area damaged, and 7% of the surface area of a mottled needle in its fifth year of growth was damaged. These values are comparable to those seen in 1975.

In summary, it can be concluded that the mottling process is now extending over the entire lifetime of a needle, whereas in 1975 it only operated during the needle's first year of growth. It can also be concluded that a larger proportion of the needles are mottled in 1980 than in 1975, although the amount of mottling present on a damaged needle is about the same as it was in 1975.

Table 15

PERCENTAGE OF NEEDLE SURFACE THAT IS DAMAGED BY MOTTLING
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1980 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	0	97	97	97	97
Maximum Value	-	6.98	11.73	45.00	63.50
Minimum Value	-	0.02	0.02	0.12	0.21
Average	-	1.81	2.84	4.39	6.29
Variance	-	3.31	5.09	27.30	72.43
Standard Deviation	-	1.82	2.26	5.22	8.51
Standard Error of Mean	-	0.18	0.23	0.53	0.86
Width of 95% Confidence Limit	-	0.37	0.45	1.05	1.72
Sample Precision	-	20.29	16.02	24.00	27.29
5% Quantile	-	0.05	0.10	0.20	0.28
25% Quantile	-	0.19	0.37	2.65	3.50
50% Quantile (Median)	-	0.95	3.15	4.20	4.75
75% Quantile	-	3.30	4.50	4.85	5.00
95% Quantile	-	4.75	5.00	10.48	17.50
Coefficient of Dispersion	-	1.83	1.79	6.22	11.52
Coefficient of Variation	-	100.64	79.49	119.06	135.37
Skewness	-	0.62	0.93	5.55	4.32
Standard Error	-	0.24	0.24	0.24	0.24
Width of 95% Confidence Limit	-	0.48	0.48	0.48	0.48
Probability of Occurrence (%)	-	1.20	0.01	0.00	0.00
Kurtosis	-	-0.97	2.52	39.28	23.41
Standard Error	-	0.49	0.49	0.49	0.49
Width of 95% Confidence Limit	-	0.95	0.95	0.95	0.95
Probability of Occurrence (%)	-	4.61	0.00	0.00	0.00
Kolmogorov-Smirnov Maximum	-	0.25	0.15	0.39	0.40
95% K-S Critical Value	-	0.14	0.14	0.14	0.14
95% Lilliefors Critical Value	-	0.09	0.09	0.09	0.09
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	-	0.02	0.02	0.12	0.21
5% Upper	-	0.09	0.13	0.32	0.38
95% Lower	-	4.40	5.00	5.00	15.92
95% Upper	-	6.98	11.73	45.00	63.50

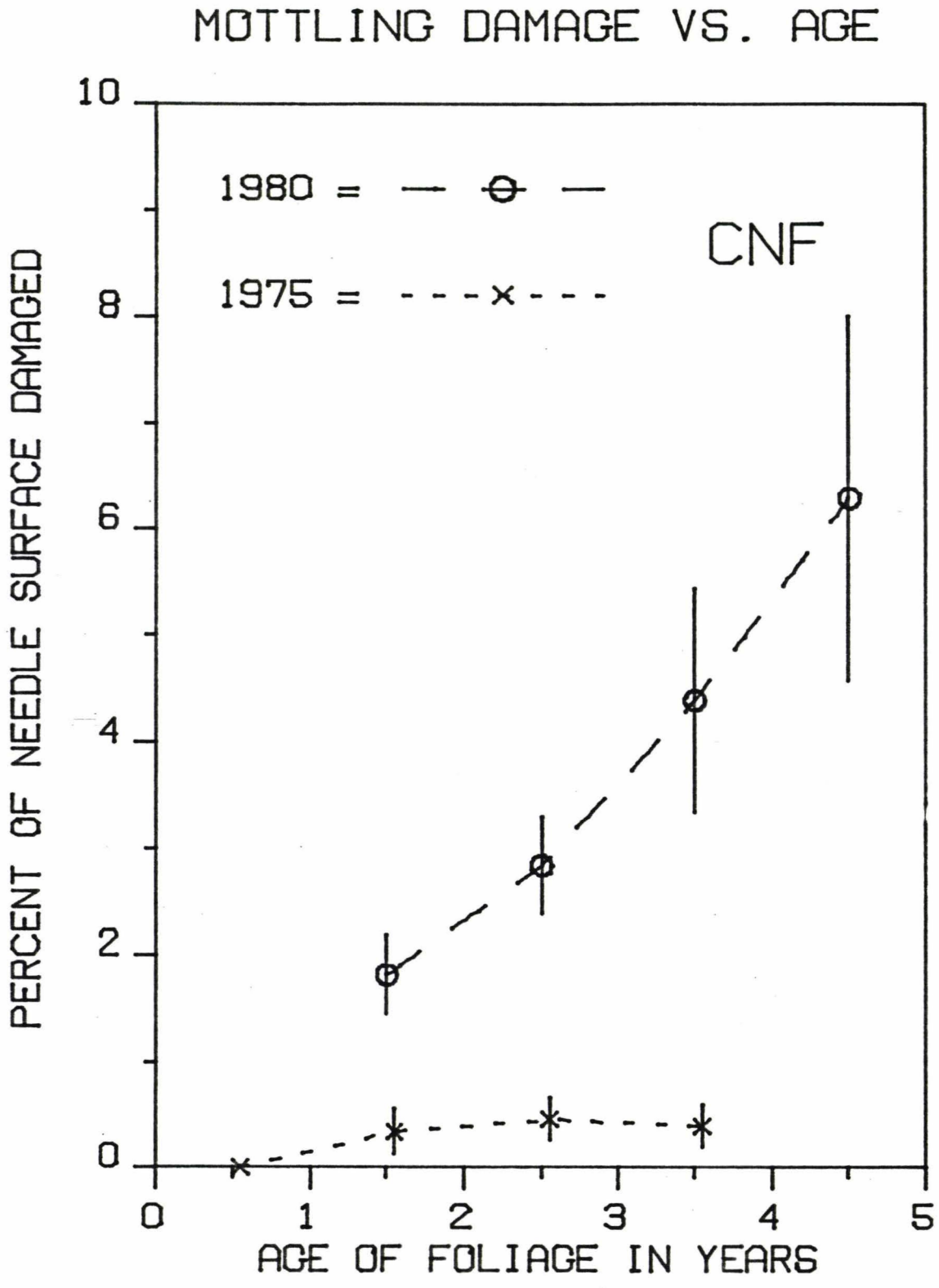

Figure 8. Percent of needle surface damaged by mottling at all CNF sites, 1975 and 1980 collections.

Just as the rate of transformation of non-tip burned needles into tip burned needles was seen to follow a first order differential equation, so too the levels of mottling seen in 1980 correspond to a first order mechanism, but the 1975 data do not. Figure 9 demonstrates these differences, It can be seen from this figure that the patterns of mottling in 1975 do not follow a first order reaction mechanism ($p \geq 0.18$). This is in accord with the hypothesis that an age selective agent (perhaps a biological one) is responsible for the mottling, for only needles in their first year of growth become mottled. This figure also shows that the 1980 data does fit the model very well ($p \leq 0.001$). The 1980 rate constant for the conversion of non-mottled needles into mottled needles is 0.371 which corresponds to a half-life of 1.9 years. This means that in 1.9 years, one-half of all the needles that are not mottled will become so. If the model is applied to the 1975 data, then the corresponding rate would be 0.021, corresponding to a half-life of 33 years.

Basal Pathologies

The ponderosa pine has a fascicular sheath covering the base of the needle fascicle where it attaches to the stem. This sheath completely envelopes the base of the needle fascicle and serves to protect the tissues that form the base of the needle. Rain, particulates, and insects that find their way into the sheath come in direct contact with the base of the needle and may cause various types of damage. Two distinct pathologies are discernible in the basal region--basal scale and basal necrosis. In 1975 these two symptoms were separately recorded. It was discovered in 1980 that some of the trees had the occurrence of both basal scale and basal necrosis lumped together under the category of basal necrosis. This necessarily complicates the discussion of differences seen in these variables in 1975 and 1980.

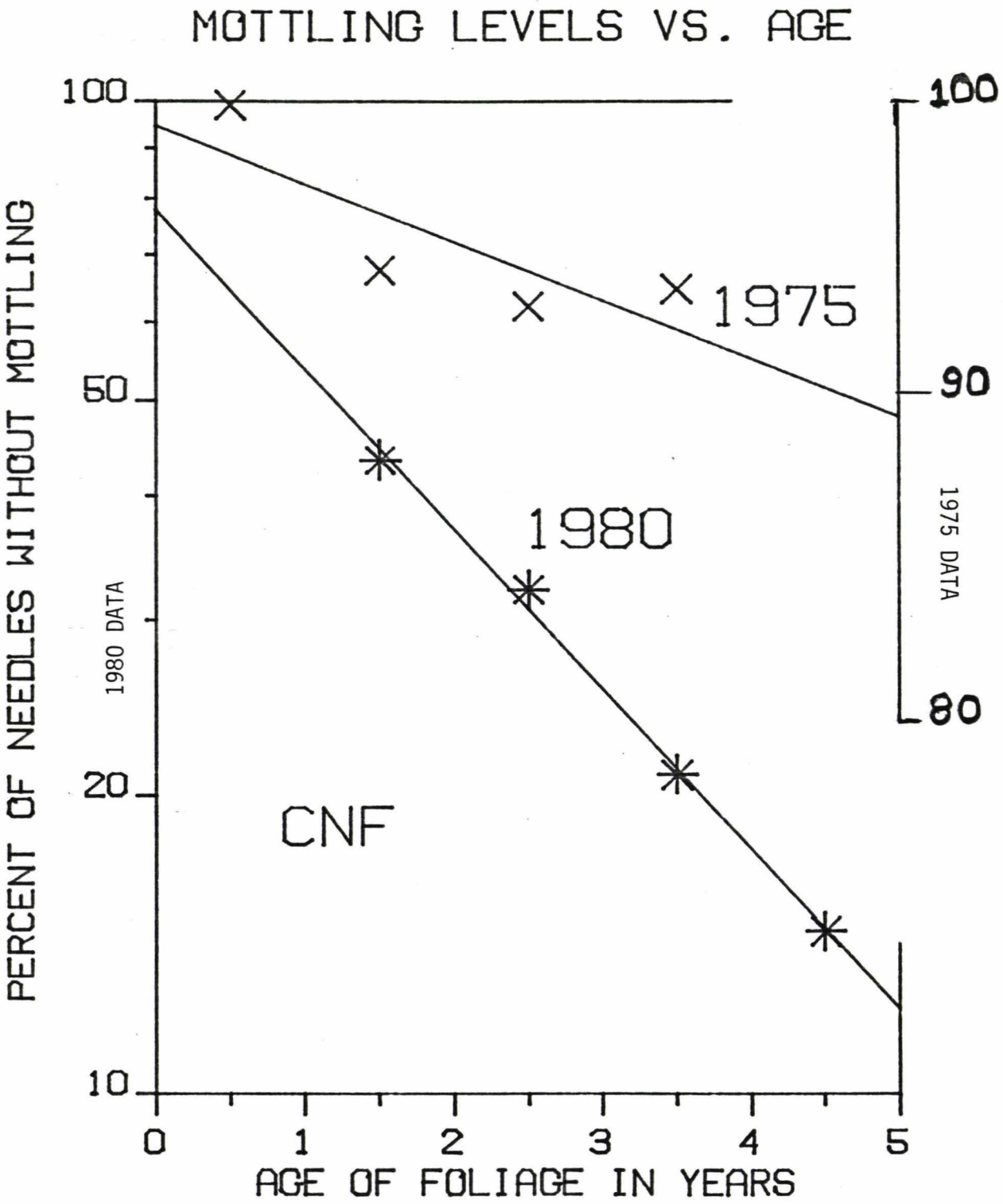

Figure 9. Levels of mottling in ponderosa pine needles at all CNF sites, 1975 and 1980 collections.

In an effort to compare the 1975 and 1980 basal pathologies, the two categories of basal pathology were combined into a composite pathology. This pathology is the presence of either scale or necrosis. The 1975 levels of basal scale and/or necrosis are almost identical to the 1980 levels. This can be seen in Table 16 which summarizes the 1975 data, Table 17 which summarizes the 1980 data, and Figure 10 which graphically portrays the data from both years of collection. The shape of the curves in Figure 10 suggests that as needles age they become afflicted with basal scale and/or necrosis at increasingly rapid rates.

This trend is seen more clearly in Figure 11 which plots the percent of needles free of both basal scale and necrosis on a logarithmic scale vs. the age of foliage. If there was a time independent probability of a needle becoming afflicted with basal scale and/or necrosis, then the graph of the logarithms of the proportions of needles free of scale and necrosis plotted against the age of foliage should be a straight line (as was the case with 1975 and 1980 tip burn levels, as well as 1980 mottling levels). The increasingly negative slope of both 1975 and 1980 data indicates that as the needles age, they become afflicted with basal scale and necrosis at increasingly rapid rates.

Weevil

The frequency of occurrence of needles with weevil damage was very similar in 1975 and 1980. Tables 18 and 19 detail the frequency of occurrence of weevil-damaged needles in 1975 and 1980, respectively. As seen in these tables, the average proportion of weevil-damaged needles was 10% in 1975 for needles in the second, third, and fourth years of growth, while the corresponding percentage in 1980 was 8%. Figure 12 shows the similarities in the

Table 16

PERCENTAGE OF NEEDLES AFFLICTED WITH BASAL SCALE AND/OR NECROSIS
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1975 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	60	130	130	130	0
Maximum Value	3.00	53.00	85.00	89.00	-
Minimum Value	0.00	0.00	0.00	0.00	-
Average	0.38	2.01	12.33	18.68	-
Variance	0.58	29.96	224.47	419.21	-
Standard Deviation	0.76	5.47	14.98	20.47	-
Standard Error of Mean	0.10	0.48	1.31	1.80	-
Width of 95% Confidence Limit	0.20	0.95	2.60	3.55	-
Sample Precision	51.31	47.32	21.09	19.03	-
5% Quantile	0.00	0.00	0.00	0.00	-
25% Quantile	0.00	0.00	2.00	4.00	-
50% Quantile (Median)	0.00	1.00	8.00	10.50	-
75% Quantile	0.50	2.00	17.00	26.00	-
95% Quantile	2.00	7.00	36.00	69.00	-
Coefficient of Dispersion	1.51	14.92	18.20	22.45	-
Coefficient of Variation	198.57	272.64	121.50	109.63	-
Skewness	2.08	7.14	2.30	1.47	-
Standard Error	0.31	0.21	0.21	0.21	-
Width of 95% Confidence Limit	0.61	0.42	0.42	0.42	-
Probability of Occurrence (%)	0.00	0.00	0.00	0.00	-
Kurtosis	3.74	61.30	6.81	1.53	-
Standard Error	0.61	0.42	0.42	0.42	-
Width of 95% Confidence Limit	1.19	0.83	0.83	0.83	-
Probability of Occurrence (%)	0.00	0.00	0.00	0.03	-
Kolmogorov-Smirnov Maximum	0.44	0.35	0.20	0.17	-
95% K-S Critical Value	0.17	0.12	0.12	0.12	-
95% Lilliefors Critical Value	0.11	0.08	0.08	0.08	-
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	0.00	0.00	0.00	0.00	-
5% Upper	0.00	0.00	0.00	1.00	-
95% Lower	1.00	5.00	33.00	50.00	-
95% Upper	3.00	26.00	76.00	80.00	-

Table 17

PERCENTAGE OF NEEDLES AFFLICTED WITH BASAL SCALE AND/OR NECROSIS
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1980 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	0	96	96	96	96
Maximum Value	-	54.00	49.00	49.00	78.00
Minimum Value	-	0.00	0.00	0.00	2.00
Average	-	4.72	7.17	12.71	29.39
Variance	-	46.63	75.68	123.89	391.57
Standard Deviation	-	6.83	8.70	11.13	19.79
Standard Error of Mean	-	0.70	0.89	1.14	2.02
Width of 95% Confidence Limit	-	1.38	1.76	2.26	4.01
Sample Precision	-	29.33	24.60	17.75	13.65
5% Quantile	-	0.00	0.00	2.00	5.00
25% Quantile	-	1.00	2.00	5.00	12.50
50% Quantile (Median)	-	3.00	4.00	9.00	23.00
75% Quantile	-	6.00	9.00	16.50	42.50
95% Quantile	-	15.00	28.00	37.00	66.00
Coefficient of Dispersion	-	9.88	10.56	9.75	13.33
Coefficient of Variation	-	144.71	121.39	87.59	67.34
Skewness	-	4.49	2.87	1.45	0.67
Standard Error	-	0.25	0.25	0.25	0.25
Width of 95% Confidence Limit	-	0.48	0.48	0.48	0.48
Probability of Occurrence (%)	-	0.00	0.00	0.00	0.62
Kurtosis	-	28.58	9.28	1.73	-0.57
Standard Error	-	0.49	0.49	0.49	0.49
Width of 95% Confidence Limit	-	0.96	0.96	0.96	0.96
Probability of Occurrence (%)	-	0.00	0.00	0.04	23.90
Kolmogorov-Smirnov Maximum	-	0.23	0.21	0.18	0.14
95% K-S Critical Value	-	0.14	0.14	0.14	0.14
95% Lilliefors Critical Value	-	0.09	0.09	0.09	0.09
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	-	0.00	0.00	0.00	2.00
5% Upper	-	0.00	1.00	2.00	8.00
95% Lower	-	11.00	14.00	30.00	61.00
95% Upper	-	54.00	49.00	49.00	78.00

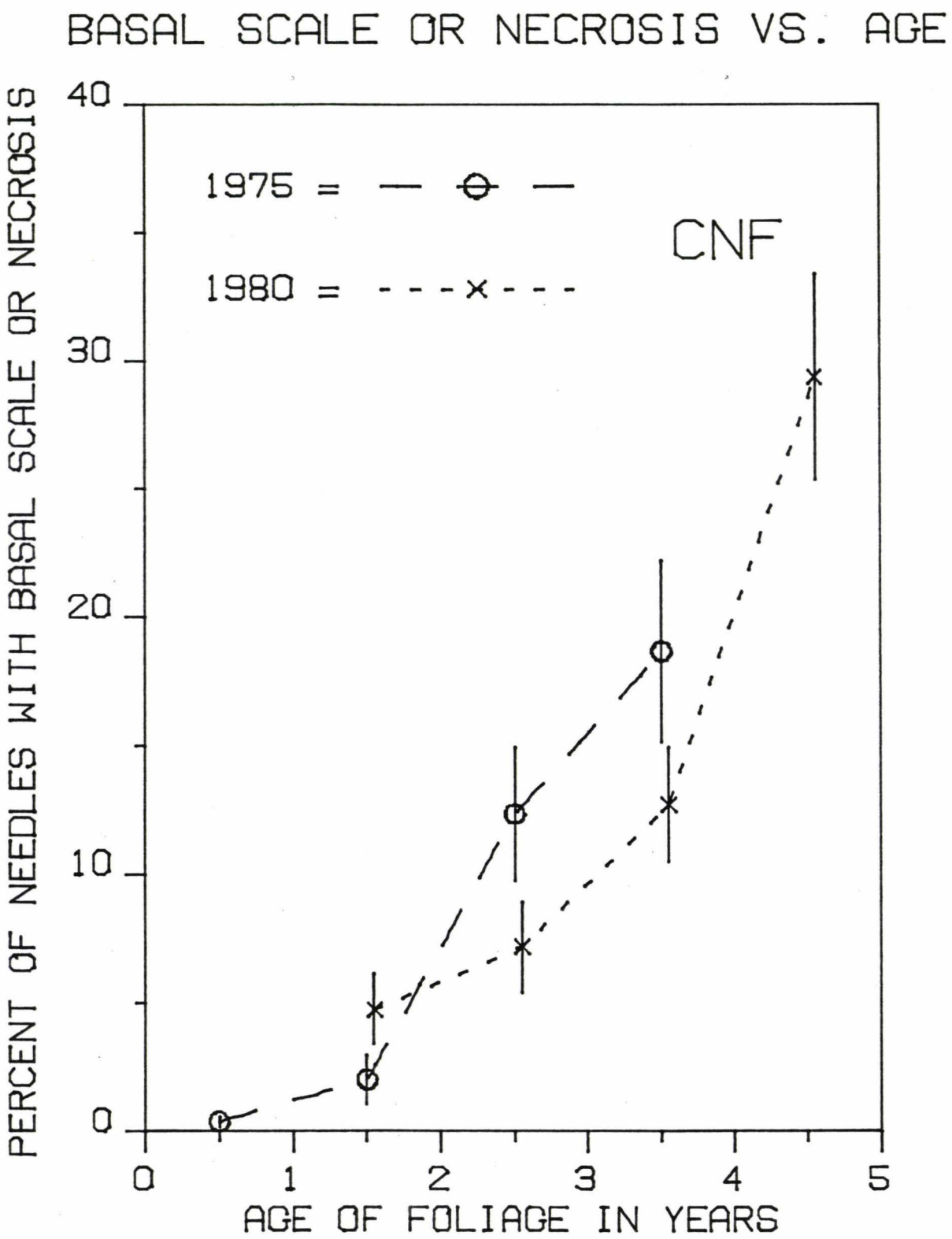

Figure 10. Percentage of ponderosa pine needles afflicted with basal scale and/or necrosis at all CNF sites, 1975 and 1980 collections.

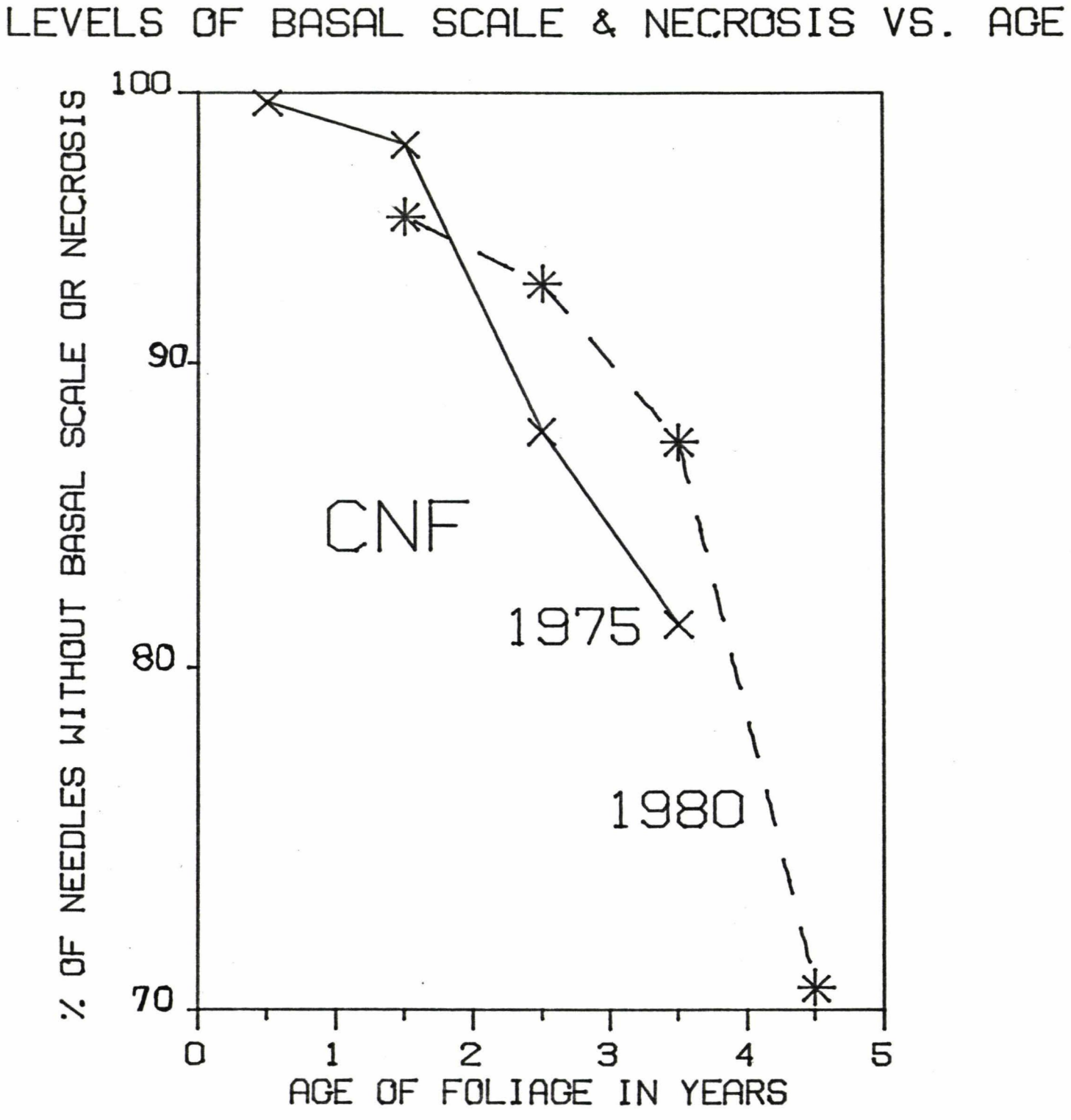

Figure 11. Levels of basal scale and/or necrosis in ponderosa pine needles at all CNF sites, 1975 and 1980 collections.

Table 18

PERCENTAGE OF NEEDLES AFFLICTED WITH WEEVIL DAMAGE
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1975 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	60	130	130	130	0
Maximum Value	10.00	57.00	50.00	50.00	-
Minimum Value	0.00	0.00	0.00	0.00	-
Average	1.62	9.08	13.07	9.57	-
Variance	4.41	76.54	123.85	71.89	-
Standard Deviation	2.10	8.75	11.13	8.48	-
Standard Error of Mean	0.27	0.77	0.98	0.74	-
Width of 95% Confidence Limit	0.54	1.52	1.93	1.47	-
Sample Precision	33.56	16.73	14.78	15.38	-
5% Quantile	0.00	0.00	0.00	0.00	-
25% Quantile	0.00	2.00	3.00	3.00	-
50% Quantile (Median)	1.00	7.00	10.00	7.50	-
75% Quantile	3.00	13.00	19.00	14.00	-
95% Quantile	5.00	25.00	32.00	28.00	-
Coefficient of Dispersion	2.73	8.43	9.48	7.51	-
Coefficient of Variation	129.90	96.38	85.15	88.61	-
Skewness	1.73	2.02	0.96	1.61	-
Standard Error	0.31	0.21	0.21	0.21	-
Width of 95% Confidence Limit	0.61	0.42	0.42	0.42	-
Probability of Occurrence (%)	0.00	0.00	0.00	0.00	-
Kurtosis	3.88	6.85	0.38	3.71	-
Standard Error	0.61	0.42	0.42	0.42	-
Width of 95% Confidence Limit	1.19	0.83	0.83	0.83	-
Probability of Occurrence (%)	0.00	0.00	36.42	0.00	-
Kolmogorov-Smirnov Maximum	0.25	0.14	0.13	0.17	-
95% K-S Critical Value	0.17	0.12	0.12	0.12	-
95% Lilliefors Critical Value	0.11	0.08	0.08	0.08	-
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	0.00	0.00	0.00	0.00	-
5% Upper	0.00	1.00	1.00	1.00	-
95% Lower	4.00	20.00	31.00	22.00	-
95% Upper	10.00	38.00	45.00	32.00	-

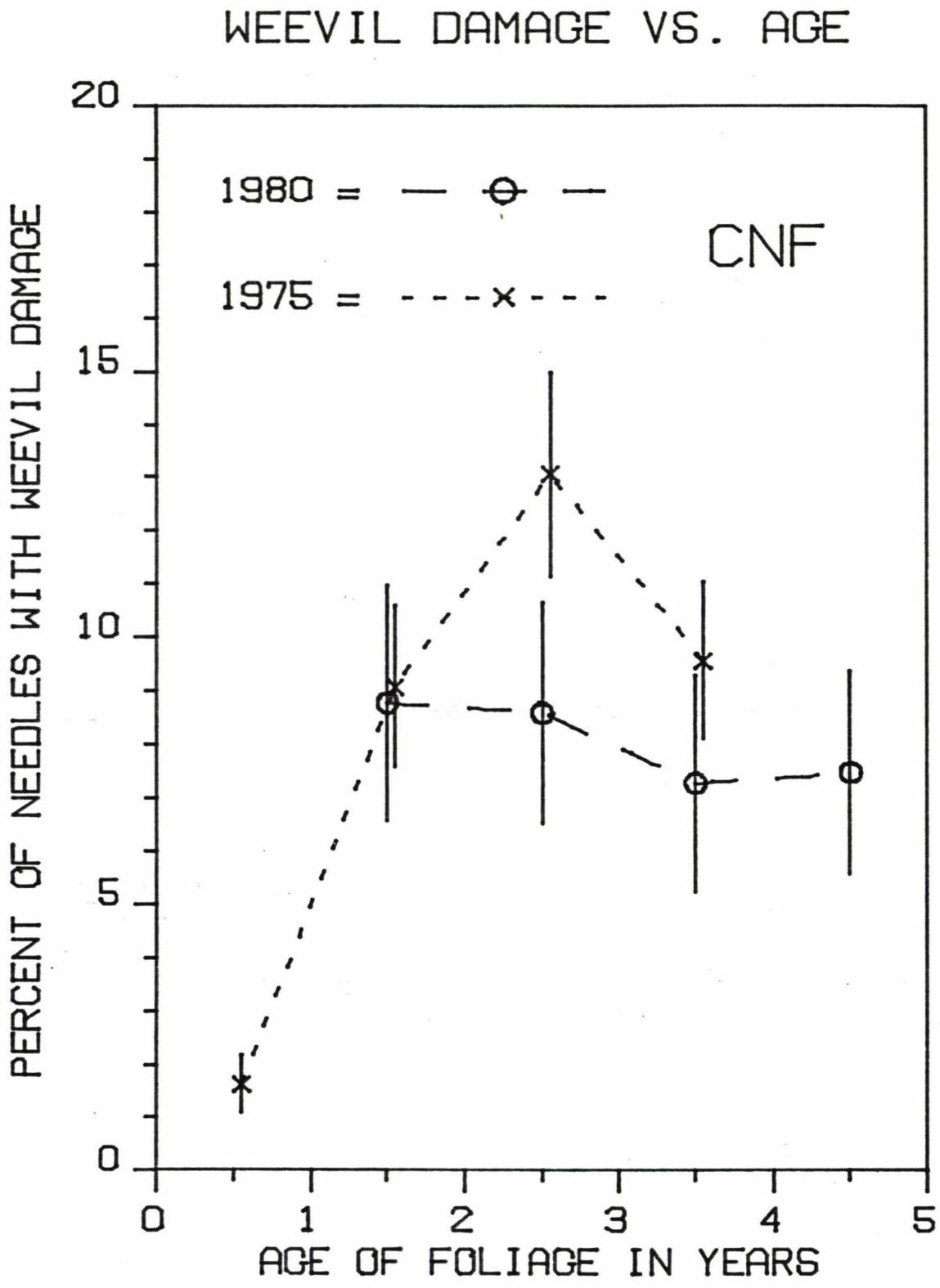

Figure 12. Percentage of ponderosa pine needles afflicted with weevil damage at all CNF sites, 1975 and 1980 collections.

patterns of weevil damage recorded in 1975 and 1980. It can be seen from this figure that, after the first year, the levels of weevil damage seem to be a constant with increasing age of foliage. This would imply that weevils do not attack all needles with equal probability. It is, rather, the first-year needles that seem to be damaged selectively, and after the first year of growth, no more weevil damage is noted.

The same picture emerges when the percentage of total foliar surface area damaged by weevils is examined. Table 20 details the proportions of total foliar surface that was damaged by weevils in 1975. Table 21 summarizes the corresponding data that was collected in 1980. It can be seen from these tables that the levels of weevil damage do not vary with increasing age (after the first year). In both tables, the average percentage of total foliar surface area that is damaged by weevils is seen to be 2%.

Figure 13 displays the data from these two tables and demonstrates the fact that the amount of needle surface area damaged by weevils does not increase after the first year but seems to be a constant.

Unclassified Pathology

Tables 22 and 23 summarize the frequency of occurrence of needles having an unclassifiable pathology in 1975 and 1980, respectively. As can be seen from these tables, the percentages of needles with an unclassified pathology was approximately 10% during 1975 and 45% during 1980. These levels are graphed in Figure 14. As shown, the levels and patterns of annual change in the number of needles with an unclassified pathology are different in 1975 and 1980. While the percentages of needles that are damaged in some miscellaneous manner rose sharply in 1980, the percent of the total foliar surface area damaged did not. Tables 24 and 25 detail the percentage of the total foliar surface area that is damaged by these unclassified pathologies in 1975

Table 20

PERCENT OF NEEDLE SURFACE DAMAGED BY WEEVILS
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1975 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	60	127	129	128	0
Maximum Value	0.70	11.25	15.00	18.75	-
Minimum Value	0.00	0.00	0.00	0.00	-
Average	0.07	1.42	2.47	1.56	-
Variance	0.02	4.23	10.63	7.49	-
Standard Deviation	0.14	2.06	3.26	2.74	-
Standard Error of Mean	0.02	0.18	0.29	0.24	-
Width of 95% Confidence Limit	0.03	0.36	0.57	0.48	-
Sample Precision	48.92	25.50	22.97	30.69	-
5% Quantile	0.00	0.00	0.00	0.01	-
25% Quantile	0.00	0.10	0.25	0.12	-
50% Quantile (Median)	0.01	0.65	1.12	0.45	-
75% Quantile	0.10	1.93	3.50	1.91	-
95% Quantile	0.38	5.60	10.50	7.75	-
Coefficient of Dispersion	0.26	2.99	4.30	4.80	-
Coefficient of Variation	189.33	145.21	131.84	175.41	-
Skewness	2.76	2.71	1.86	3.41	-
Standard Error	0.31	0.21	0.21	0.21	-
Width of 95% Confidence Limit	0.61	0.42	0.42	0.42	-
Probability of Occurrence (%)	0.00	0.00	0.00	0.00	-
Kurtosis	8.64	8.85	3.26	14.62	-
Standard Error	0.61	0.43	0.42	0.42	-
Width of 95% Confidence Limit	1.19	0.84	0.83	0.83	-
Probability of Occurrence (%)	0.00	0.00	0.00	0.00	-
Kolmogorov-Smirnov Maximum	0.31	0.24	0.22	0.28	-
95% K-S Critical Value	0.17	0.12	0.12	0.12	-
95% Lilliefors Critical Value	0.11	0.08	0.08	0.08	-
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	0.00	0.00	0.00	0.00	-
5% Upper	0.00	0.01	0.01	0.01	-
95% Lower	0.20	3.68	7.13	4.50	-
95% Upper	0.70	10.88	14.25	11.63	-

Table 21

PERCENT OF NEEDLE SURFACE DAMAGED BY WEEVILS
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1980 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	0	97	97	97	97
Maximum Value	-	22.50	31.88	22.50	20.25
Minimum Value	-	0.00	0.00	0.00	0.00
Average	-	2.18	2.09	1.58	1.58
Variance	-	16.14	18.10	12.26	10.38
Standard Deviation	-	4.02	4.25	3.50	3.22
Standard Error of Mean	-	0.41	0.43	0.36	0.33
Width of 95% Confidence Limit	-	0.81	0.86	0.71	0.65
Sample Precision	-	37.10	41.00	44.78	41.10
5% Quantile	-	0.00	0.00	0.00	0.00
25% Quantile	-	0.18	0.15	0.10	0.10
50% Quantile (Median)	-	0.75	0.52	0.52	0.35
75% Quantile	-	1.92	2.10	1.22	1.40
95% Quantile	-	10.88	10.88	11.25	9.75
Coefficient of Dispersion	-	7.39	8.65	7.78	6.57
Coefficient of Variation	-	184.03	203.41	222.12	203.90
Skewness	-	3.22	4.42	3.94	3.46
Standard Error	-	0.24	0.24	0.24	0.24
Width of 95% Confidence Limit	-	0.48	0.48	0.48	0.48
Probability of Occurrence (%)	-	0.00	0.00	0.00	0.00
Kurtosis	-	11.23	25.67	17.09	13.74
Standard Error	-	0.49	0.49	0.49	0.49
Width of 95% Confidence Limit	-	0.95	0.95	0.95	0.95
Probability of Occurrence (%)	-	0.00	0.00	0.00	0.00
Kolmogorov-Smirnov Maximum	-	0.29	0.30	0.34	0.31
95% K-S Critical Value	-	0.14	0.14	0.14	0.14
95% Lilliefors Critical Value	-	0.09	0.09	0.09	0.09
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	-	0.00	0.00	0.00	0.00
5% Upper	-	0.00	0.00	0.00	0.00
95% Lower	-	5.88	6.38	3.38	5.95
95% Upper	-	22.50	31.88	22.50	20.25

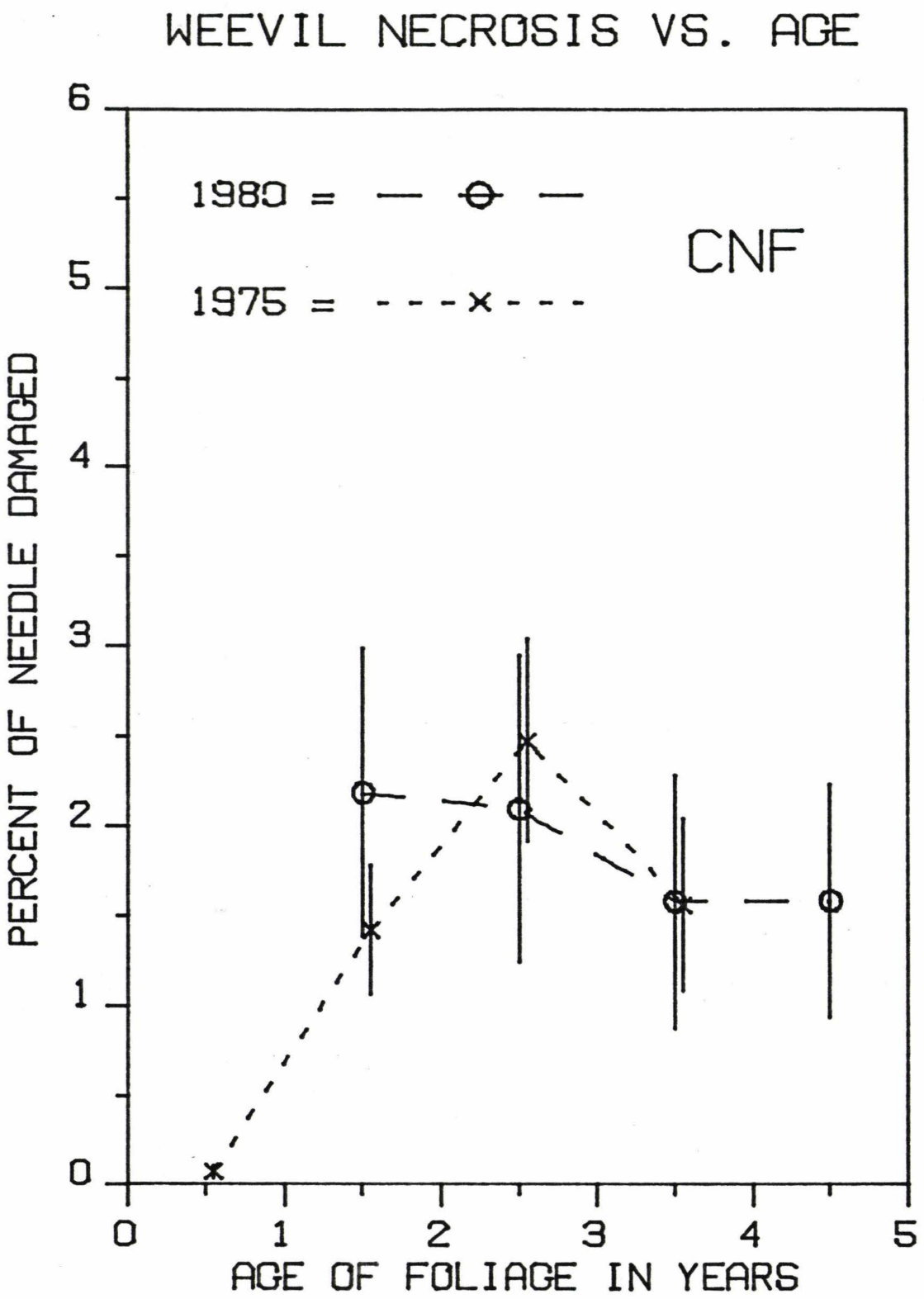

Figure 13. Percent of ponderosa pine needle surface damaged by weevils at all CNF sites, 1975 and 1980 collections.

Table 22

PERCENTAGE OF NEEDLES AFFLICTED WITH AN UNCLASSIFIED PATHOLOGY
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1975 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	60	130	130	130	0
Maximum Value	46.00	56.00	55.00	66.00	-
Minimum Value	0.00	0.00	0.00	0.00	-
Average	2.53	8.94	13.68	12.58	-
Variance	49.20	147.28	198.11	185.50	-
Standard Deviation	7.01	12.14	14.08	13.62	-
Standard Error of Mean	0.91	1.06	1.23	1.19	-
Width of 95% Confidence Limit	1.81	2.11	2.44	2.36	-
Sample Precision	71.54	23.57	17.85	18.80	-
5% Quantile	0.00	0.00	0.00	0.00	-
25% Quantile	0.00	1.00	1.00	2.00	-
50% Quantile (Median)	0.00	4.00	10.00	9.00	-
75% Quantile	2.00	11.00	20.00	19.00	-
95% Quantile	14.00	38.00	45.00	41.00	-
Coefficient of Dispersion	19.42	16.48	14.48	14.75	-
Coefficient of Variation	276.89	135.77	102.85	108.29	-
Skewness	4.82	1.89	1.05	1.61	-
Standard Error	0.31	0.21	0.21	0.21	-
Width of 95% Confidence Limit	0.61	0.42	0.42	0.42	-
Probability of Occurrence (%)	0.00	0.00	0.00	0.00	-
Kurtosis	26.49	3.04	0.29	2.81	-
Standard Error	0.61	0.42	0.42	0.42	-
Width of 95% Confidence Limit	1.19	0.83	0.83	0.83	-
Probability of Occurrence (%)	0.00	0.00	49.72	0.00	-
Kolmogorov-Smirnov Maximum	0.36	0.26	0.16	0.17	-
95% K-S Critical Value	0.17	0.12	0.12	0.12	-
95% Lilliefors Critical Value	0.11	0.08	0.08	0.08	-
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	0.00	0.00	0.00	0.00	-
5% Upper	0.00	0.00	0.00	0.00	-
95% Lower	5.00	29.00	37.00	31.00	-
95% Upper	46.00	47.00	51.00	60.00	-

Table 23

PERCENTAGE OF NEEDLES AFFLICTED WITH AN UNCLASSIFIED PATHOLOGY
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1980 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	0	96	96	96	96
Maximum Value	-	99.00	98.00	100.00	98.00
Minimum Value	-	4.00	6.00	7.00	7.00
Average	-	39.01	42.80	45.24	54.31
Variance	-	345.80	361.02	500.31	459.56
Standard Deviation	-	18.60	19.00	22.37	21.44
Standard Error of Mean	-	1.90	1.94	2.28	2.19
Width of 95% Confidence Limit	-	3.77	3.85	4.53	4.34
Sample Precision	-	9.66	9.00	10.02	8.00
5% Quantile	-	15.00	15.00	12.00	16.00
25% Quantile	-	26.00	31.50	29.00	41.00
50% Quantile (Median)	-	33.50	43.00	41.00	51.50
75% Quantile	-	49.50	53.00	59.00	68.00
95% Quantile	-	78.00	76.00	85.00	94.00
Coefficient of Dispersion	-	8.86	8.43	11.06	8.46
Coefficient of Variation	-	47.67	44.39	49.44	39.47
Skewness	-	0.88	0.52	0.46	0.09
Standard Error	-	0.25	0.25	0.25	0.25
Width of 95% Confidence Limit	-	0.48	0.48	0.48	0.48
Probability of Occurrence (%)	-	0.03	3.51	5.95	70.98
Kurtosis	-	0.67	0.45	-0.45	-0.46
Standard Error	-	0.49	0.49	0.49	0.49
Width of 95% Confidence Limit	-	0.96	0.96	0.96	0.96
Probability of Occurrence (%)	-	16.65	35.36	36.07	34.33
Kolmogorov-Smirnov Maximum	-	0.15	0.08	0.09	0.06
95% K-S Critical Value	-	0.14	0.14	0.14	0.14
95% Lilliefors Critical Value	-	0.09	0.09	0.09	0.09
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	-	4.00	6.00	7.00	7.00
5% Upper	-	18.00	17.00	15.00	26.00
95% Lower	-	68.00	72.00	79.00	90.00
95% Upper	-	99.00	98.00	100.00	98.00

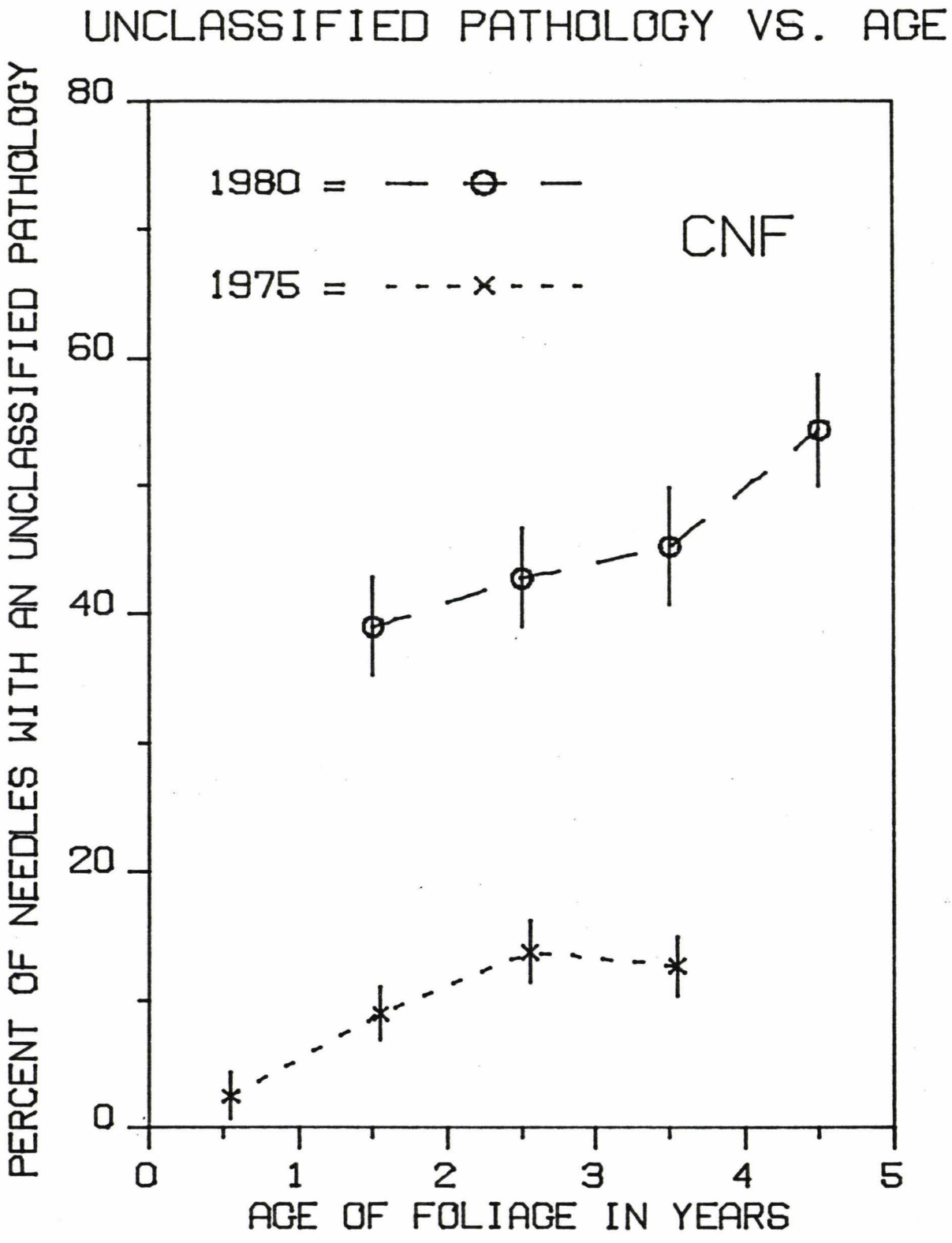

Figure 14. Percentage of ponderosa pine needles afflicted with an unclassified pathology at all CNF sites, 1975 and 1980 collections.

Table 24

PERCENT OF NEEDLE SURFACE DAMAGED BY UNCLASSIFIED PATHOLOGY
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1975 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	59	127	130	129	0
Maximum Value	3.38	18.10	27.83	33.38	-
Minimum Value	0.00	0.00	0.00	0.00	-
Average	0.25	1.39	2.27	2.78	-
Variance	0.35	8.31	21.95	25.08	-
Standard Deviation	0.59	2.88	4.69	5.01	-
Standard Error of Mean	0.08	0.26	0.41	0.44	-
Width of 95% Confidence Limit	0.15	0.51	0.81	0.87	-
Sample Precision	60.68	36.44	35.84	31.35	-
5% Quantile	0.00	0.00	0.00	0.00	-
25% Quantile	0.00	0.03	0.05	0.07	-
50% Quantile (Median)	0.01	0.40	0.85	1.05	-
75% Quantile	0.15	1.40	1.93	2.98	-
95% Quantile	1.20	9.67	9.71	13.28	-
Coefficient of Dispersion	1.37	5.98	9.68	9.01	-
Coefficient of Variation	232.80	207.45	206.52	179.89	-
Skewness	3.60	3.49	3.83	3.50	-
Standard Error	0.31	0.21	0.21	0.21	-
Width of 95% Confidence Limit	0.61	0.42	0.42	0.42	-
Probability of Occurrence (%)	0.00	0.00	0.00	0.00	-
Kurtosis	15.22	13.22	15.79	14.56	-
Standard Error	0.61	0.43	0.42	0.42	-
Width of 95% Confidence Limit	1.20	0.84	0.83	0.83	-
Probability of Occurrence (%)	0.00	0.00	0.00	0.00	-
Kolmogorov-Smirnov Maximum	0.35	0.31	0.31	0.28	-
95% K-S Critical Value	0.17	0.12	0.12	0.12	-
95% Lilliefors Critical Value	0.12	0.08	0.08	0.08	-
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	0.00	0.00	0.00	0.00	-
5% Upper	0.00	0.00	0.00	0.00	-
95% Lower	0.70	3.75	6.65	8.58	-
95% Upper	3.38	12.38	26.30	23.50	-

Table 25

PERCENTAGE OF NEEDLE SURFACE THAT IS DAMAGED BY AN UNCLASSIFIED PATHOLOGY
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1980 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	0	97	97	97	97
Maximum Value	-	7.05	6.70	11.26	29.99
Minimum Value	-	0.08	0.15	0.19	0.08
Average	-	2.31	2.36	2.91	4.51
Variance	-	2.76	2.32	3.46	12.26
Standard Deviation	-	1.66	1.52	1.86	3.50
Standard Error of Mean	-	0.17	0.15	0.19	0.36
Width of 95% Confidence Limit	-	0.34	0.31	0.37	0.71
Sample Precision	-	14.51	13.01	12.89	15.63
5% Quantile	-	0.17	0.24	0.41	0.68
25% Quantile	-	1.13	1.03	1.61	2.69
50% Quantile (Median)	-	2.00	2.19	2.57	4.17
75% Quantile	-	3.13	3.57	4.00	5.50
95% Quantile	-	6.07	5.00	5.85	7.90
Coefficient of Dispersion	-	1.20	0.98	1.19	2.72
Coefficient of Variation	-	71.97	64.53	63.93	77.55
Skewness	-	0.85	0.57	1.18	4.33
Standard Error	-	0.24	0.24	0.24	0.24
Width of 95% Confidence Limit	-	0.48	0.48	0.48	0.48
Probability of Occurrence (%)	-	0.05	2.02	0.00	0.00
Kurtosis	-	0.28	-0.30	3.17	29.16
Standard Error	-	0.49	0.49	0.49	0.49
Width of 95% Confidence Limit	-	0.95	0.95	0.95	0.95
Probability of Occurrence (%)	-	55.81	53.35	0.00	0.00
Kolmogorov-Smirnov Maximum	-	0.10	0.08	0.08	0.16
95% K-S Critical Value	-	0.14	0.14	0.14	0.14
95% Lilliefors Critical Value	-	0.09	0.09	0.09	0.09
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	-	0.08	0.15	0.19	0.08
5% Upper	-	0.27	0.44	0.70	1.43
95% Lower	-	4.68	4.46	5.00	7.05
95% Upper	-	7.05	6.70	11.26	29.99

and 1980, respectively. Both tables show that in 1975 and 1980 about 2.5% of the total foliar surface area of the needles was damaged. Figure 15 shows this same data, and the similarity between the two years of collection can be seen at once.

Healthy Needles

Given the fact that there was a large increase in the number of needles afflicted with both tip burn and mottling in 1980, it is not surprising to find a correspondingly large drop in the number of healthy needles seen in 1980. Table 26 summarizes the 1975 data, and it can be seen that 72% of the second-year needles and 49% of the fourth-year needles were still healthy at the time of collection. Table 27 summarizes the corresponding 1980 data and shows that 13% of the second-year and 3% of the fourth-year needles were healthy at the time of collection.

The proportion of all needles that were still healthy at the time of collection during 1975 and 1980 are contrasted in Figure 16. As shown, needles continue to become unhealthy throughout their lifetime. This primarily reflects the continued accumulation of tip burned and mottled needles. Further insight can be gained by replotting the data shown in Figure 16 on a logarithmic axis. This has been done in Figure 17 which shows that the rate at which a needle becomes unhealthy is independent of the age of a needle. The overall rate constant for the disappearance of healthy needles was .2295 in 1975, corresponding to a half-life of three years. In 1980 the overall rate constant for the disappearance of healthy needles was 0.7827, corresponding to a half-life of 0.9 years.

Because individual rate constants are additive, the sum of the rate constants for tip burn, mottling, basal damage, weevil damage, and unclassified damage should add up to a value close to the overall rate of

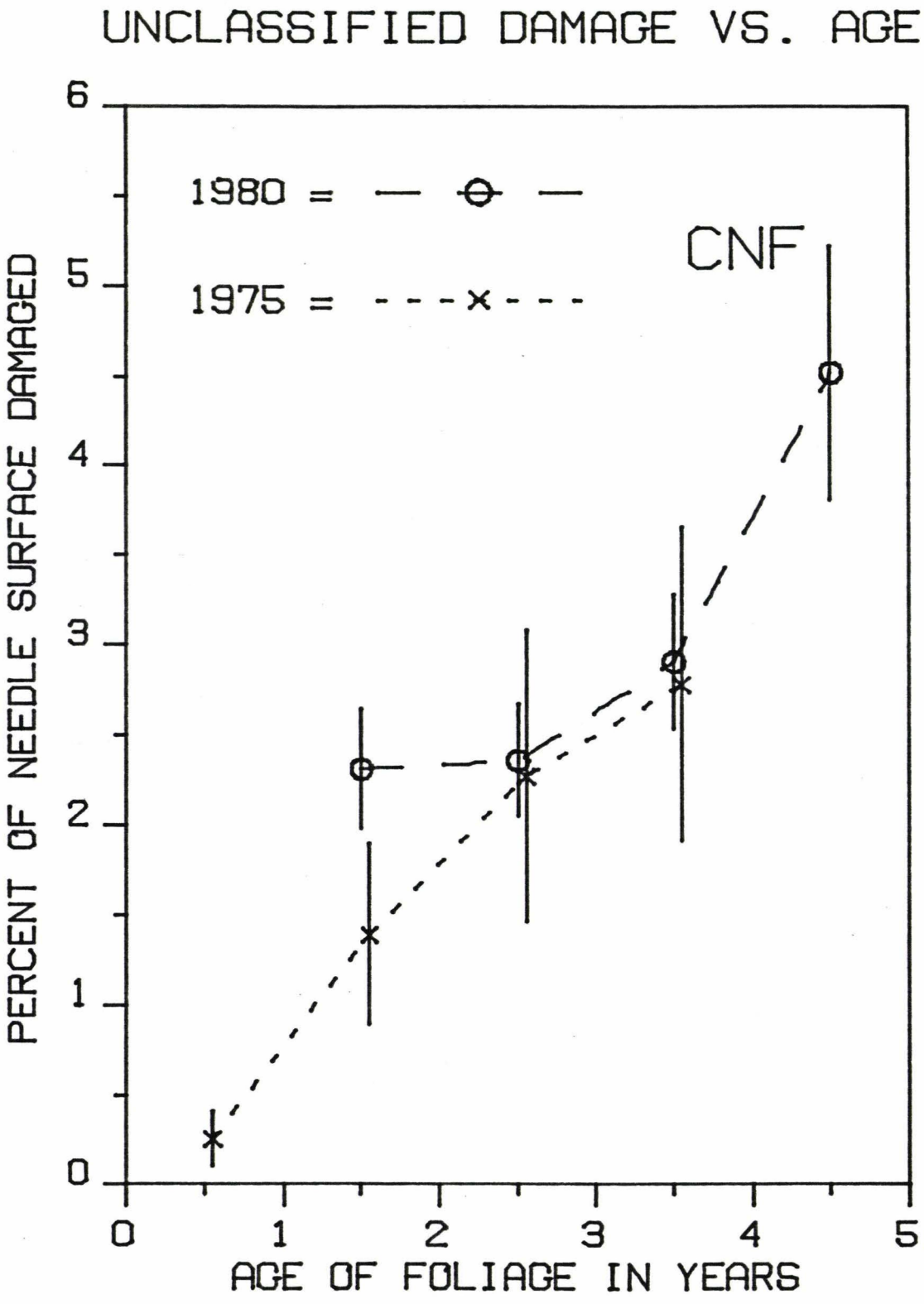

Figure 15. Percent of ponderosa pine needle surface damaged by unclassified pathology at all CNF sites, 1975 and 1980 collections.

Table 26

PERCENTAGE OF ALL NEEDLES THAT ARE HEALTHY
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1975 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	60	130	130	130	0
Maximum Value	100.00	100.00	94.00	95.00	-
Minimum Value	53.00	0.00	0.00	0.00	-
Average	94.02	71.81	52.22	48.66	-
Variance	57.68	404.65	479.64	565.68	-
Standard Deviation	7.59	20.12	21.90	23.78	-
Standard Error of Mean	0.98	1.76	1.92	2.09	-
Width of 95% Confidence Limit	1.96	3.49	3.80	4.13	-
Sample Precision	2.09	4.86	7.28	8.48	-
5% Quantile	80.00	32.00	17.00	5.00	-
25% Quantile	92.50	60.00	38.00	33.00	-
50% Quantile (Median)	97.00	77.00	51.50	50.00	-
75% Quantile	98.00	87.00	70.00	68.00	-
95% Quantile	100.00	95.00	86.00	84.00	-
Coefficient of Dispersion	0.61	5.64	9.19	11.62	-
Coefficient of Variation	8.08	28.01	41.94	48.88	-
Skewness	-3.24	-1.00	-0.21	-0.20	-
Standard Error	0.31	0.21	0.21	0.21	-
Width of 95% Confidence Limit	0.61	0.42	0.42	0.42	-
Probability of Occurrence (%)	0.00	0.00	31.72	33.84	-
Kurtosis	14.22	0.59	-0.52	-0.76	-
Standard Error	0.61	0.42	0.42	0.42	-
Width of 95% Confidence Limit	1.19	0.83	0.83	0.83	-
Probability of Occurrence (%)	0.00	16.22	21.70	7.23	-
Kolmogorov-Smirnov Maximum	0.22	0.10	0.06	0.05	-
95% K-S Critical Value	0.17	0.12	0.12	0.12	-
95% Lilliefors Critical Value	0.11	0.08	0.08	0.08	-
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	53.00	19.00	0.00	0.00	-
5% Upper	88.00	38.00	20.00	14.00	-
95% Lower	100.00	94.00	83.00	81.00	-
95% Upper	100.00	98.00	92.00	91.00	-

Table 27

PERCENTAGE OF ALL NEEDLES THAT ARE HEALTHY
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1980 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	0	96	96	96	96
Maximum Value	-	51.00	45.00	39.00	19.00
Minimum Value	-	0.00	0.00	0.00	0.00
Average	-	12.58	5.36	3.38	1.08
Variance	-	182.86	99.01	56.85	10.75
Standard Deviation	-	13.52	9.95	7.54	3.28
Standard Error of Mean	-	1.38	1.02	0.77	0.33
Width of 95% Confidence Limit	-	2.74	2.02	1.53	0.66
Sample Precision	-	21.78	37.59	45.28	61.34
5% Quantile	-	0.00	0.00	0.00	0.00
25% Quantile	-	0.00	0.00	0.00	0.00
50% Quantile (Median)	-	9.00	0.00	0.00	0.00
75% Quantile	-	20.00	5.50	2.00	0.00
95% Quantile	-	43.00	35.00	21.00	6.00
Coefficient of Dispersion	-	14.53	18.46	16.84	9.92
Coefficient of Variation	-	107.46	185.49	223.40	302.66
Skewness	-	1.02	2.39	3.02	3.97
Standard Error	-	0.25	0.25	0.25	0.25
Width of 95% Confidence Limit	-	0.48	0.48	0.48	0.48
Probability of Occurrence (%)	-	0.00	0.00	0.00	0.00
Kurtosis	-	0.14	5.33	9.50	17.07
Standard Error	-	0.49	0.49	0.49	0.49
Width of 95% Confidence Limit	-	0.96	0.96	0.96	0.96
Probability of Occurrence (%)	-	77.45	0.00	0.00	0.00
Kolmogorov-Smirnov Maximum	-	0.17	0.28	0.33	0.46
95% K-S Critical Value	-	0.14	0.14	0.14	0.14
95% Lilliefors Critical Value	-	0.09	0.09	0.09	0.09
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	-	0.00	0.00	0.00	0.00
5% Upper	-	0.00	0.00	0.00	0.00
95% Lower	-	36.00	20.00	13.00	5.00
95% Upper	-	51.00	45.00	39.00	19.00

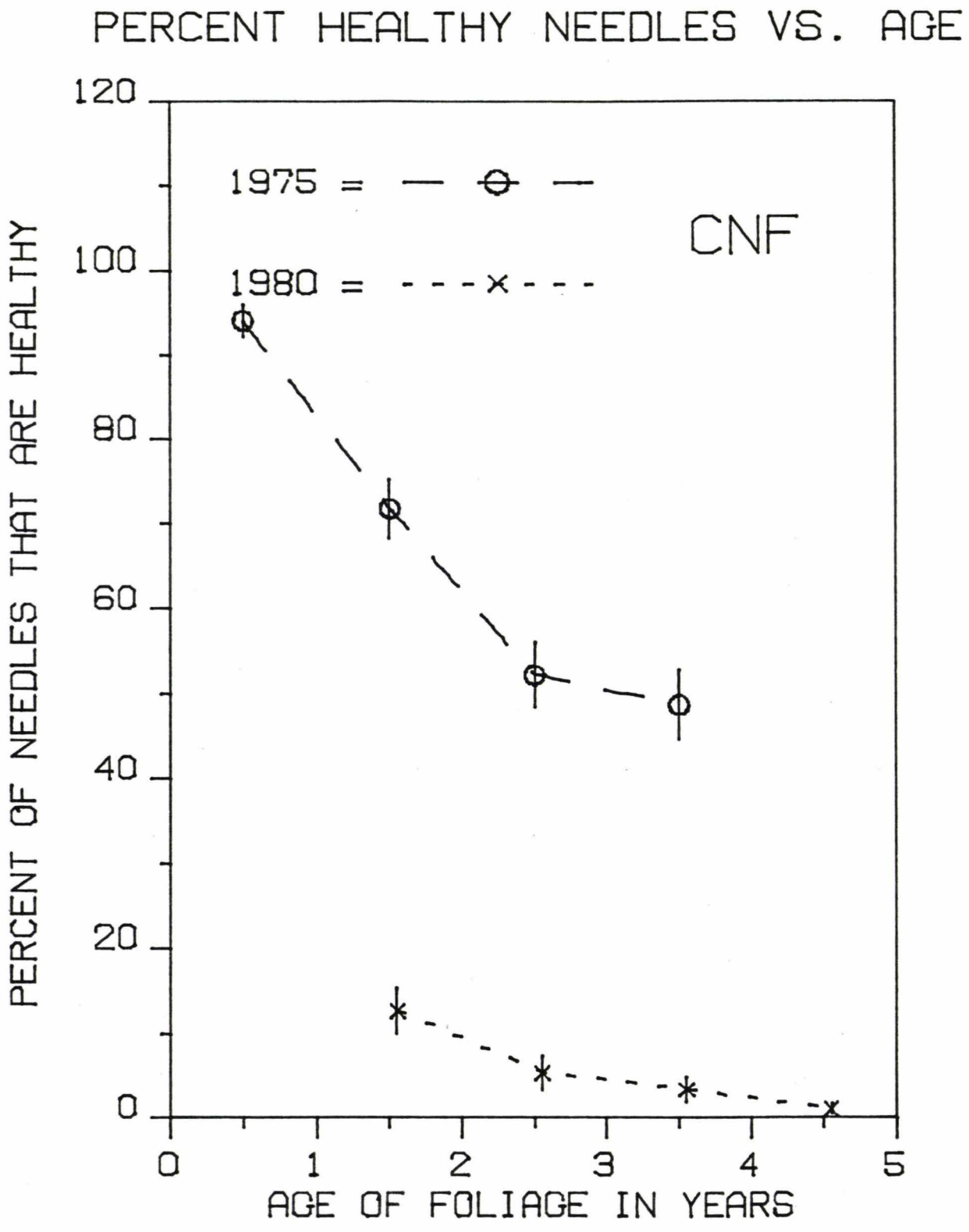

Figure 16. Percentage of all ponderosa pine needles that are healthy at all CNF sites, 1975 and 1980 collections.

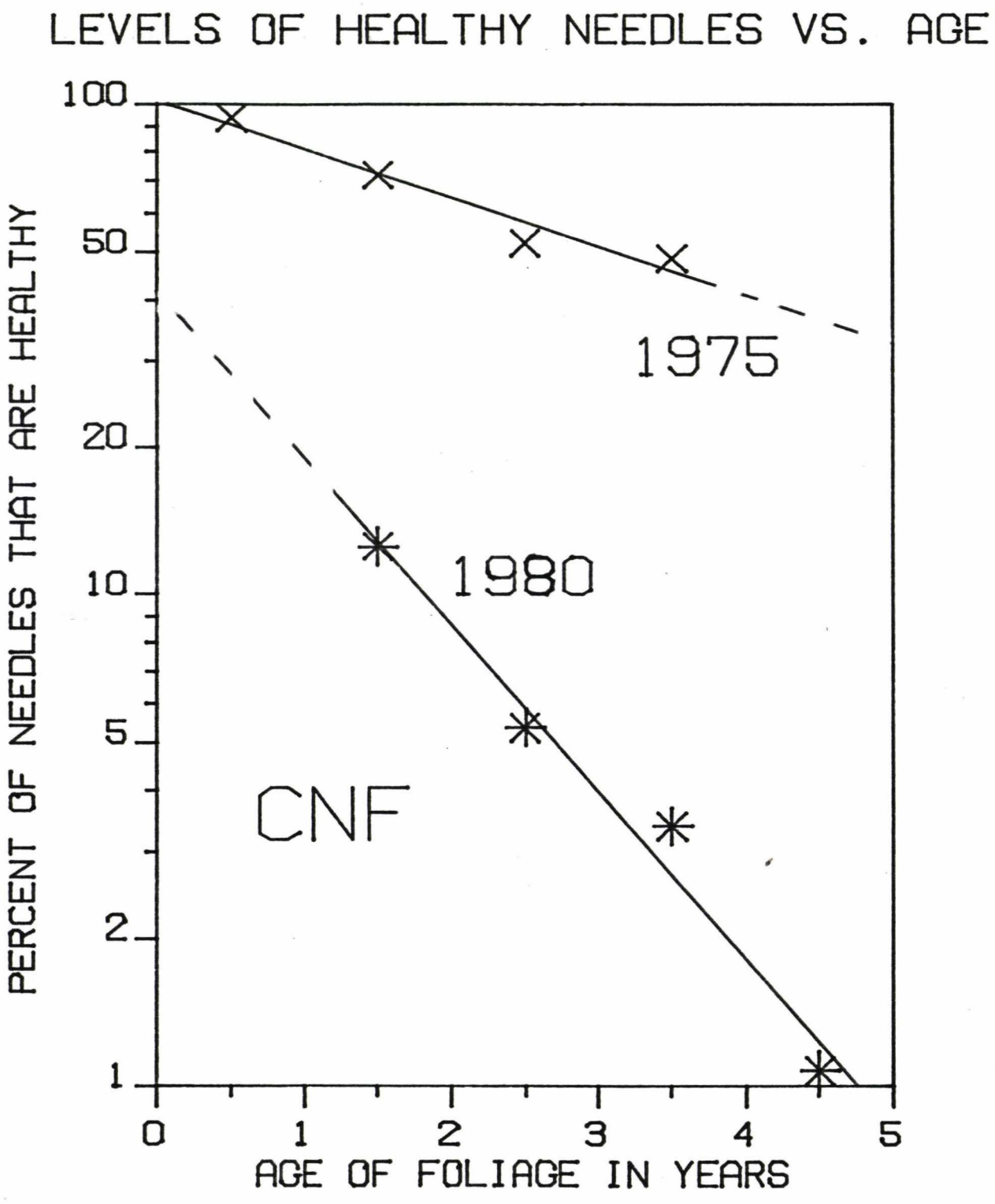

Figure 17. Levels of healthy ponderosa pine needles at all CNF sites, 1975 and 1980 collections.

disappearance of healthy needles, indicating that the overall rate of appearance of unhealthy needles is a consequence of the above-mentioned individual pathologies. The sum of the 1975 individual reaction rates is 0.18 compared to the overall rate of 0.23, while the sum of the 1980 reaction rates is 0.78 which equals the overall rate. For the additivity of reaction rates to hold exactly, then a needle must have exactly one pathology at any given time. This is obviously not the case. The main point raised by this line of analysis is, however, that the frequency of occurrence of some of the variables studied can be considered to be first order reactions, and that the sum of these processes is responsible for the overall disappearance of healthy needles.

The employment of analysis of variance to quantify any differences between levels of healthy needles in 1975 and 1980 is complicated by the change in the nature of the distributions of healthy needles, both as the needles age and from collection to collection. This is most readily seen in the measures of the data's skewness, as shown in Tables 26 and 27. In general, as the foliage increases in age, the data becomes progressively skewed to the right. This is indicated by the fact that the skewness increased from -3.2 for the first-year needles to -0.2 for needles in their fourth year of growth. In 1980 the data once again shows increasing skewness with increasing age, rising from +1.0 in the second year of growth to +4.0 in the fifth year of growth.

The results of the ANOVA are presented in Table 28. Given the different natures of the levels of healthy needles, both between ages in a given collection and between collection, it is not surprising to find highly significant ($p < 0.001$) differences between sites, collections, and ages, as well as site-collection, age-site, and collection-age interactions.

Table 28

Comparisons of Healthy Needles in 1975 and 1980 Collections Over Custer National Forest Sites
Three-Factor ANOVA with Repeated Measures on Collection and Age of Foliage

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Value	Probability of Occurrence
Between Trees					
Site (S)	20,346	9	2,260	4.11	0.0002
Error	47,269	86	549		
Within Trees					
Collection (C)	372,715	1	372,715	875.95	<0.0001
CxS	25,242	9	2,804	6.59	<0.0001
Error	36,592	86	425		
Age (A)	32,106	2	16,053	142.49	<0.0001
AxS	6,580	18	365	3.24	<0.0001
Error	19,377	172	112		
CxA	7,872	2	3,936	38.17	<0.0001
CxAxS	6,991	18	388	3.77	<0.0001
Error	17,737	172	103		

Total Needle Necrosis

Along with a decrease in the number of healthy needles present on the pine trees examined in 1980 relative to 1975 went a corresponding increase in the percentage of the total foliar surface area that was damaged. Table 29 summarizes the 1975 data and indicates that the average proportion of the total foliar surface area that is damaged by pathologies varies from 3% for needles in their second year of growth to 5% for needles in their fourth year of growth.

Table 30 details the corresponding data collected in 1980. This table shows that the levels of total necrosis increased to 6.6% of the total foliar surface area for needles in their second year of growth and was 15.6% in the fifth year needles. These data are graphically portrayed in Figure 18. It is seen in this figure that the overall levels of needle damage are higher in 1980 than 1975. This figure also suggests that the amount of needle damage rises throughout the life of the needles in 1980, whereas in the 1975 data the amount of needle damage reaches a maximum after two years of growth.

To further define the nature of the changes seen in the levels of total necrosis between the 1975 and 1980 collections, an analysis of variance was performed. Table 31 presents the results of this analysis. As can be seen, there are significant ($p < 0.001$) differences between both collections and ages, and there are significant collection-site and age-site interactions. There is no significant differences ($p > 0.05$) between sites, however, and the collection-age interaction is non-significant. This casts doubt on the significance of the leveling off of needle damage in the third and fourth years of growth, as shown in Figure 18 for the 1975 data.

Table 29

PERCENTAGE OF NEEDLE SURFACE THAT IS DAMAGED BY PATHOLOGIES
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1975 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	60	127	130	129	0
Maximum Value	3.60	22.30	33.32	34.90	-
Minimum Value	0.00	0.00	0.00	0.00	-
Average	0.33	3.18	5.39	5.11	-
Variance	0.40	17.22	33.51	33.04	-
Standard Deviation	0.63	4.15	5.79	5.75	-
Standard Error of Mean	0.08	0.37	0.51	0.51	-
Width of 95% Confidence Limit	0.16	0.73	1.00	1.00	-
Sample Precision	48.90	22.94	18.64	19.59	-
5% Quantile	0.00	0.06	0.30	0.10	-
25% Quantile	0.00	0.80	1.60	1.40	-
50% Quantile (Median)	0.02	1.80	3.60	3.30	-
75% Quantile	0.40	3.70	7.10	6.30	-
95% Quantile	1.25	11.60	16.50	18.90	-
Coefficient of Dispersion	1.20	5.42	6.22	6.46	-
Coefficient of Variation	189.27	130.58	107.37	112.44	-
Skewness	3.21	2.70	2.15	2.37	-
Standard Error	0.31	0.21	0.21	0.21	-
Width of 95% Confidence Limit	0.61	0.42	0.42	0.42	-
Probability of Occurrence (%)	0.00	0.00	0.00	0.00	-
Kurtosis	12.75	8.08	5.71	6.88	-
Standard Error	0.61	0.43	0.42	0.42	-
Width of 95% Confidence Limit	1.19	0.84	0.83	0.83	-
Probability of Occurrence (%)	0.00	0.00	0.00	0.00	-
Kolmogorov-Smirnov Maximum	0.28	0.23	0.18	0.20	-
95% K-S Critical Value	0.17	0.12	0.12	0.12	-
95% Lilliefors Critical Value	0.11	0.08	0.08	0.08	-
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	0.00	0.00	0.04	0.00	-
5% Upper	0.00	0.15	0.50	0.50	-
95% Lower	1.20	8.60	13.30	12.60	-
95% Upper	3.60	21.60	27.10	25.00	-

Table 30

PERCENTAGE OF NEEDLE SURFACE THAT IS DAMAGED BY PATHOLOGIES
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1980 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	0	97	97	97	97
Maximum Value	-	24.81	33.99	54.75	97.99
Minimum Value	-	0.69	0.70	1.44	0.05
Average	-	6.63	8.60	10.62	15.61
Variance	-	21.16	25.19	55.53	155.70
Standard Deviation	-	4.60	5.02	7.45	12.48
Standard Error of Mean	-	0.47	0.51	0.76	1.27
Width of 95% Confidence Limit	-	0.93	1.01	1.50	2.52
Sample Precision	-	13.99	11.77	14.15	16.12
5% Quantile	-	1.16	1.19	2.29	3.15
25% Quantile	-	3.70	5.68	6.10	9.50
50% Quantile (Median)	-	5.77	8.23	9.17	12.96
75% Quantile	-	7.82	10.87	12.42	18.33
95% Quantile	-	16.53	17.38	23.65	30.25
Coefficient of Dispersion	-	3.19	2.93	5.23	9.98
Coefficient of Variation	-	69.40	58.38	70.20	79.96
Skewness	-	1.54	1.45	2.63	3.60
Standard Error	-	0.24	0.24	0.24	0.24
Width of 95% Confidence Limit	-	0.48	0.48	0.48	0.48
Probability of Occurrence (%)	-	0.00	0.00	0.00	0.00
Kurtosis	-	2.90	5.63	12.08	19.97
Standard Error	-	0.49	0.49	0.49	0.49
Width of 95% Confidence Limit	-	0.95	0.95	0.95	0.95
Probability of Occurrence (%)	-	0.00	0.00	0.00	0.00
Kolmogorov-Smirnov Maximum	-	0.16	0.10	0.16	0.20
95% K-S Critical Value	-	0.14	0.14	0.14	0.14
95% Lilliefors Critical Value	-	0.09	0.09	0.09	0.09
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	-	0.69	0.70	1.44	0.05
5% Upper	-	1.77	2.13	3.85	5.33
95% Lower	-	13.95	14.89	19.60	28.84
95% Upper	-	24.81	33.99	54.75	97.99

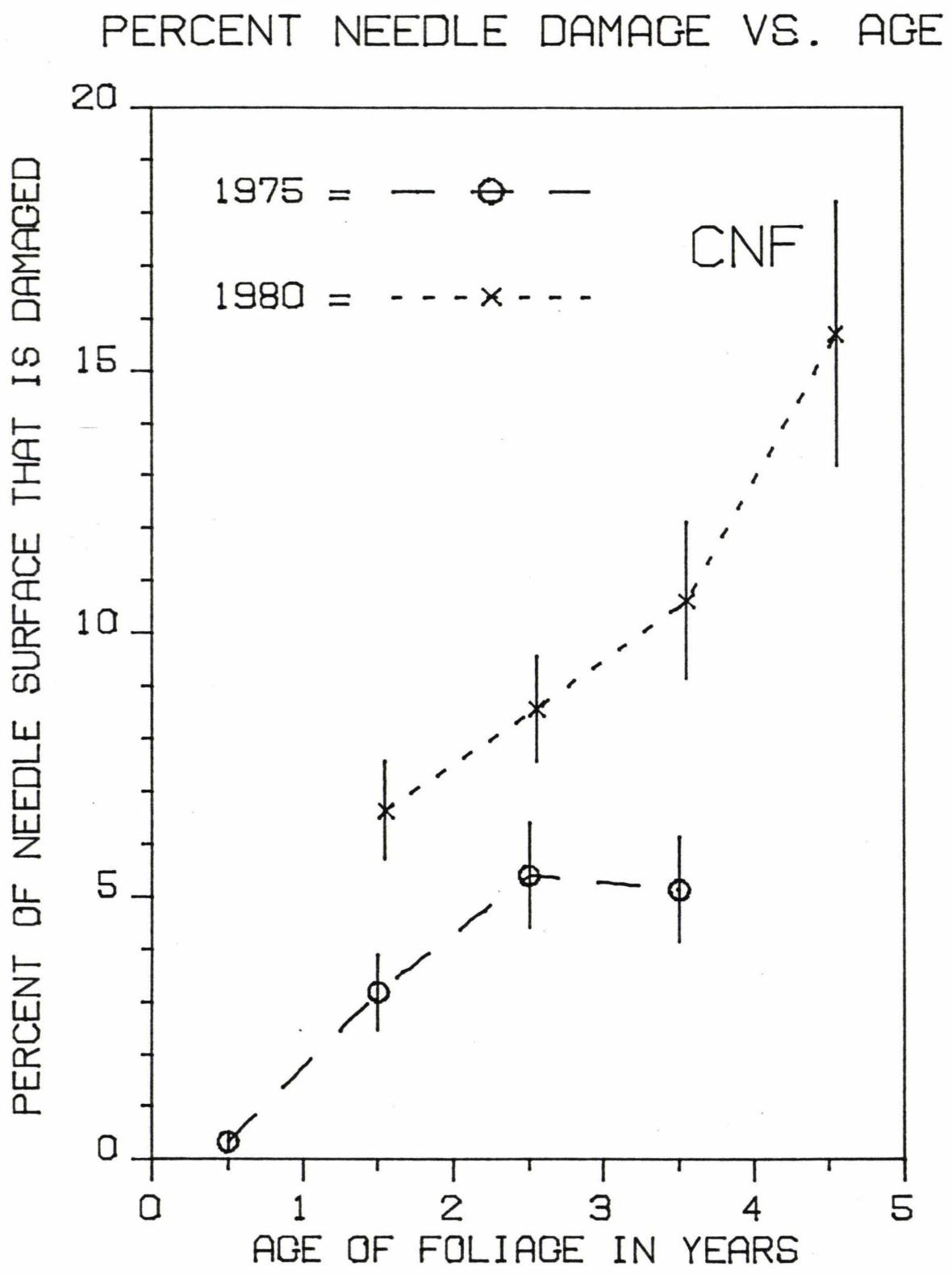

Figure 18. Percentage of ponderosa pine needle surface that is damaged by pathologies at all CNF sites, 1975 and 1980 collections.

Table 31

Comparisons of Total Necrosis in 1975 and 1980 Collections Over Custer National Forest Sites
Three-Factor ANOVA with Repeated Measures on Collection and Age of Foliage*

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Value	Probability of Occurrence
Between Trees					
Site (S)	2.540	9	0.282	1.50	0.1624
Error	15.645	83	0.188		
Within Trees					
Collection (C)	15.152	1	15.152	174.85	<0.0001
CxS	10.526	9	1.169	13.50	<0.0001
Error	7.192	83	0.086		
Age (A)	3.115	2	1.557	43.63	<0.0001
AxS	1.879	18	0.104	2.92	0.0002
Error	5.925	166	0.035		
CxA	0.134	2	0.067	1.98	0.1415
CxAxS	1.110	18	0.061	1.82	0.0264
Error	5.622	166	0.033		

*Raw data was normalized by taking the logarithms of data prior to analysis.

Needle Retention

Perhaps one of the better known responses to chronic air pollution is a decrease in needle retention. Table 32 summarizes the 1975 data and indicates that the needle retention drops from 95% for needles in their second year of growth to 84% for needles in their fourth year of growth. The corresponding data collected in 1980 is shown in Table 33 and indicates that the overall levels of needle retention fell in 1980 from what they were in 1975. Reference to Table 33 shows that only 86% of the needles were retained into the second year of growth, and 73% of the needles were retained into the fifth year of growth.

Figure 19 presents a comparison of the 1975 and 1980 data. It is shown on this graph that the second-year needles display the greatest drop in needle retention, but the other years are very similar. To further characterize the changes seen in the amount of needle retention in 1980 relative to 1975, an analysis of variance was performed. The results of this analysis are presented in Table 34. Based on the significant ($p < 0.01$) site, age, and collection differences, as well as the collection-age interaction, it can be concluded that needle retention decreases with increasing age, and there are differences between the sites and the collections are different as well. It can also be concluded that the age responses are different in 1975 and 1980.

Needle Length

Table 35 summarizes the average length of pine needles in 1975 by age of foliage. As can be seen in this table, the average needle lengths are normally distributed, perhaps reflecting the fact that these estimates are averages of 25 individual needle lengths (the central limit theorem states that as the sample size increases, the means of samples drawn from a population of any distribution will approach the normal distribution). In 1975

Table 32

AVERAGE PERCENT NEEDLE RETENTION
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1975 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	60	130	130	130	0
Maximum Value	100.00	100.00	100.00	100.00	-
Minimum Value	88.80	51.00	45.00	18.00	-
Average	98.30	95.18	88.89	84.18	-
Variance	6.41	49.33	123.97	287.79	-
Standard Deviation	2.53	7.02	11.13	16.96	-
Standard Error of Mean	0.33	0.62	0.98	1.49	-
Width of 95% Confidence Limit	0.65	1.22	1.93	2.94	-
Sample Precision	0.67	1.28	2.17	3.50	-
5% Quantile	92.75	83.00	68.00	47.00	-
25% Quantile	98.00	93.00	82.00	77.00	-
50% Quantile (Median)	99.50	98.00	93.00	90.00	-
75% Quantile	100.00	100.00	97.80	96.80	-
95% Quantile	100.00	100.00	100.00	99.25	-
Coefficient of Dispersion	0.07	0.52	1.39	3.42	-
Coefficient of Variation	2.57	7.38	12.53	20.15	-
Skewness	-1.86	-2.91	-1.34	-1.67	-
Standard Error	0.31	0.21	0.21	0.21	-
Width of 95% Confidence Limit	0.61	0.42	0.42	0.42	-
Probability of Occurrence (%)	0.00	0.00	0.00	0.00	-
Kurtosis	3.33	12.46	1.60	2.85	-
Standard Error	0.61	0.42	0.42	0.42	-
Width of 95% Confidence Limit	1.19	0.83	0.83	0.83	-
Probability of Occurrence (%)	0.00	0.00	0.01	0.00	-
Kolmogorov-Smirnov Maximum	0.25	0.25	0.18	0.18	-
95% K-S Critical Value	0.17	0.12	0.12	0.12	-
95% Lilliefors Critical Value	0.11	0.08	0.08	0.08	-
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	88.80	73.00	57.00	23.00	-
5% Upper	95.00	85.00	73.00	59.30	-
95% Lower	100.00	100.00	99.00	99.00	-
95% Upper	100.00	100.00	100.00	100.00	-

Table 33

AVERAGE PERCENT NEEDLE RETENTION
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1980 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	0	95	95	95	95
Maximum Value	-	100.00	100.00	96.70	96.60
Minimum Value	-	38.00	56.94	52.10	34.90
Average	-	86.45	88.64	85.03	72.99
Variance	-	255.13	84.99	113.45	218.12
Standard Deviation	-	15.97	9.22	10.65	14.77
Standard Error of Mean	-	1.64	0.95	1.09	1.52
Width of 95% Confidence Limit	-	3.25	1.88	2.17	3.01
Sample Precision	-	3.76	2.12	2.55	4.12
5% Quantile	-	50.50	69.25	61.90	42.79
25% Quantile	-	82.30	82.00	81.38	62.70
50% Quantile (Median)	-	92.61	90.15	88.20	74.20
75% Quantile	-	98.40	96.50	92.90	84.60
95% Quantile	-	99.60	99.20	96.30	93.58
Coefficient of Dispersion	-	2.95	0.96	1.33	2.99
Coefficient of Variation	-	18.48	10.40	12.53	20.23
Skewness	-	-1.45	-1.13	-1.34	-0.65
Standard Error	-	0.25	0.25	0.25	0.25
Width of 95% Confidence Limit	-	0.49	0.49	0.49	0.49
Probability of Occurrence (%)	-	0.00	0.00	0.00	0.83
Kurtosis	-	1.21	1.17	1.26	-0.18
Standard Error	-	0.49	0.49	0.49	0.49
Width of 95% Confidence Limit	-	0.96	0.96	0.96	0.96
Probability of Occurrence (%)	-	1.36	1.70	1.01	70.78
Kolmogorov-Smirnov Maximum	-	0.20	0.12	0.14	0.11
95% K-S Critical Value	-	0.14	0.14	0.14	0.14
95% Lilliefors Critical Value	-	0.09	0.09	0.09	0.09
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	-	38.00	56.94	52.10	34.90
5% Upper	-	55.95	76.00	65.70	50.54
95% Lower	-	99.46	98.20	95.40	89.03
95% Upper	-	100.00	100.00	96.70	96.60

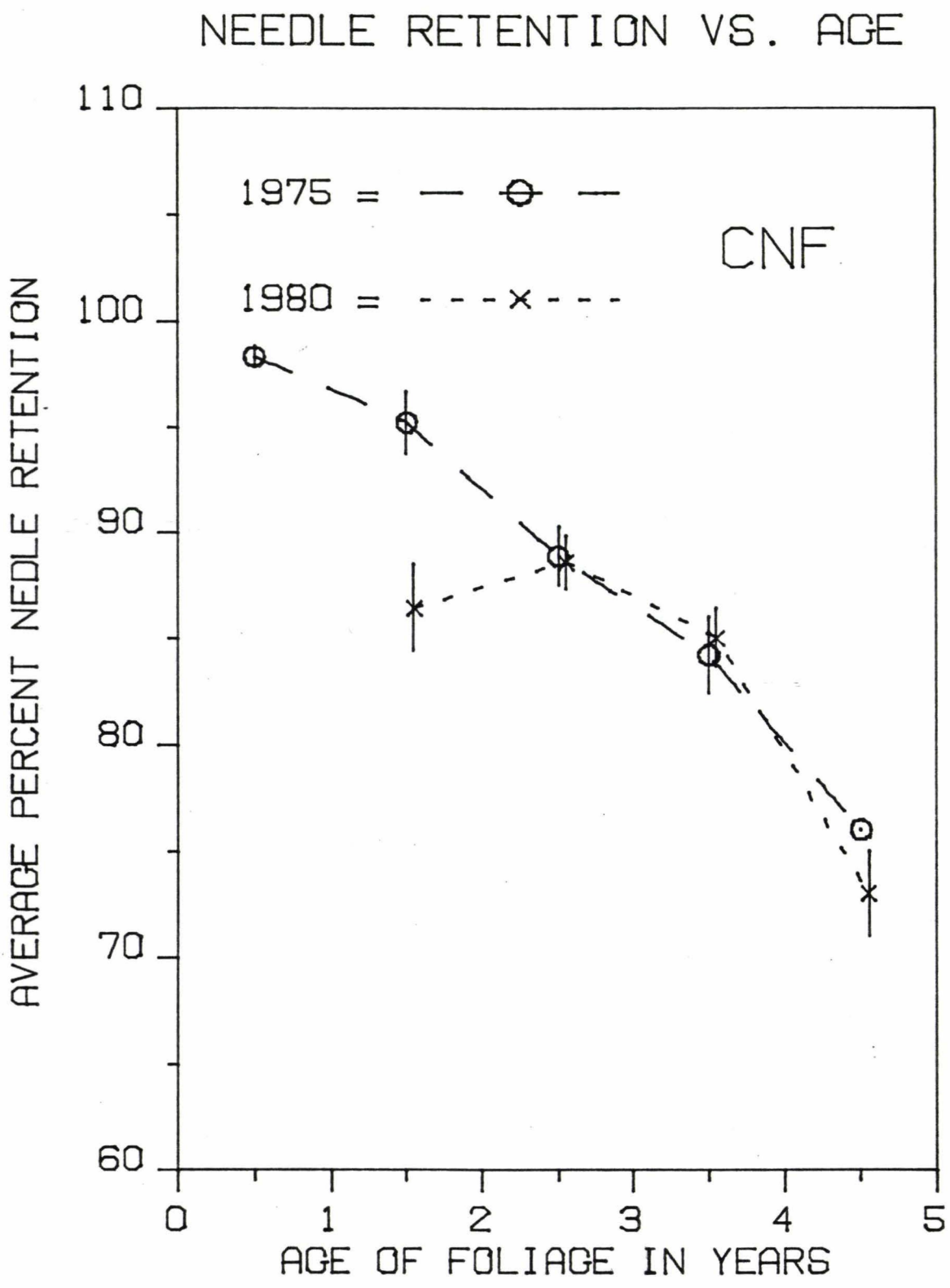

Figure 19. Average percent ponderosa pine needle retention at all CNF sites, 1975 and 1980 collections.

Table 34

Comparisons of Needle Retention in 1975 and 1980 Collections Over Custer National Forest Sites
Three-Factor ANOVA with Repeated Measures on Collection and Age of Foliage

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Value	Probability of Occurrence
Between Trees					
Site (S)	7,232	9	803	2.67	0.0089
Error	25,617	85	301		
Within Trees					
Collection (C)	1,630	1	1,630	9.42	0.0029
CxS	1,214	9	134	0.78	0.6352
Error	14,708	85	173		
Age (A)	3,421	2	1,710	18.53	<0.0001
AxS	2,364	18	131	1.42	0.1261
Error	15,691	170	92		
CxA	2,268	2	1,134	12.41	<0.0001
CxAxS	2,233	18	124	1.36	0.1586
Error	15,532	170	91		

Table 35

AVERAGE NEEDLE LENGTH (MILLIMETERS)
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1975 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	60	129	130	130	0
Maximum Value	189.20	184.00	185.00	183.80	-
Minimum Value	87.60	70.40	90.70	84.80	-
Average	141.45	129.98	137.92	129.49	-
Variance	451.44	505.95	336.35	374.18	-
Standard Deviation	21.25	22.49	18.34	19.34	-
Standard Error of Mean	2.74	1.98	1.61	1.70	-
Width of 95% Confidence Limit	5.49	3.92	3.18	3.36	-
Sample Precision	3.88	3.02	2.31	2.59	-
5% Quantile	107.05	91.80	108.10	93.84	-
25% Quantile	129.95	114.40	127.92	116.68	-
50% Quantile (Median)	140.85	130.40	136.75	130.40	-
75% Quantile	156.20	145.30	151.80	142.20	-
95% Quantile	174.40	166.60	165.30	162.10	-
Coefficient of Dispersion	3.19	3.89	2.44	2.89	-
Coefficient of Variation	15.02	17.31	13.30	14.94	-
Skewness	-0.06	-0.16	-0.09	0.17	-
Standard Error	0.31	0.21	0.21	0.21	-
Width of 95% Confidence Limit	0.61	0.42	0.42	0.42	-
Probability of Occurrence (%)	83.98	44.30	67.76	42.03	-
Kurtosis	-0.28	-0.06	0.02	0.22	-
Standard Error	0.61	0.42	0.42	0.42	-
Width of 95% Confidence Limit	1.19	0.83	0.83	0.83	-
Probability of Occurrence (%)	64.37	89.45	96.97	59.76	-
Kolmogorov-Smirnov Maximum	0.06	0.06	0.05	0.05	-
95% K-S Critical Value	0.17	0.12	0.12	0.12	-
95% Lilliefors Critical Value	0.11	0.08	0.08	0.08	-
95% Confidence Limits of Selected Quantiles					
5% Lower	87.60	75.60	93.00	86.80	-
5% Upper	111.80	99.40	112.40	104.60	-
95% Lower	172.20	159.00	161.10	156.80	-
95% Upper	189.20	180.50	184.20	183.60	-

the overall average needle length was 134.7 mm. Table 36 portrays the needle length data collected in 1980. The overall average was slightly higher in 1980 than it was in 1975, being 139.9 mm.

The range of observed needle lengths serves as an estimate of the amount of inherent variation in mean needle length that can be induced by the sum total of factors that determine the ultimate length of a growing needle. Figure 20 graphically portrays the data presented in Tables 35 and 36. It can be seen from this figure that there are large differences in the average needle lengths seen for the various year's needles. To emphasize the idea that a needle's length is primarily determined during its first year of growth, the year that each of the needles first began to grow is listed with each year's mean needle length. An analysis of variance was performed upon these data and the results are presented in Table 37. As shown, there are differences between sites, collections, and ages. This is in accord with the patterns of needle lengths seen in Figure 20.

Dry Weight Per Needle

Table 38 characterizes the average dry weight of a needle in 1975 for the various years of foliage. It can be seen in this table that the average dry weight of one needle fluctuated between 69.9 mg for a needle that emerged in 1974 to 84.4 mg for a needle that emerged in 1973, with an overall average of 78 mg per needle. Figure 21 displays the average needle weight as a function of age of foliage. As can be seen, the average needle weight fluctuates each year, and once again the year of emergence is placed on the graph to facilitate its comparison with needle length and cross sectional area data (Figures 20 and 22).

Table 36

AVERAGE NEEDLE LENGTH (MILLIMETERS)
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1980 COLLECTION

		Year of Foliage			
	First	Second	Third	Fourth	Fifth
Sample Size	0	97	97	97	97
Maximum Value	-	198.84	198.68	178.28	209.72
Minimum Value	-	86.00	76.44	62.64	97.68
Average	-	146.45	143.47	122.73	146.79
Variance	-	387.74	345.44	474.44	324.37
Standard Deviation	-	19.69	18.59	21.78	18.01
Standard Error of Mean	-	2.00	1.89	2.21	1.83
Width of 95% Confidence Limit	-	3.97	3.75	4.39	3.63
Sample Precision	-	2.71	2.61	3.58	2.47
5% Quantile	-	116.68	116.16	88.20	117.00
25% Quantile	-	134.56	131.32	109.68	133.80
50% Quantile (Median)	-	143.68	143.44	119.24	148.00
75% Quantile	-	159.00	153.16	136.00	157.56
95% Quantile	-	181.64	175.60	160.36	178.52
Coefficient of Dispersion	-	2.65	2.41	3.87	2.21
Coefficient of Variation	-	13.45	12.95	17.75	12.27
Skewness	-	0.20	-0.05	0.04	0.14
Standard Error	-	0.24	0.24	0.24	0.24
Width of 95% Confidence Limit	-	0.48	0.48	0.48	0.48
Probability of Occurrence (%)	-	41.48	85.40	87.23	55.48
Kurtosis	-	0.56	1.52	0.21	1.03
Standard Error	-	0.49	0.49	0.49	0.49
Width of 95% Confidence Limit	-	0.95	0.95	0.95	0.95
Probability of Occurrence (%)	-	24.89	0.17	67.20	3.44
Kolmogorov-Smirnov Maximum	-	0.10	0.07	0.08	0.07
95% K-S Critical Value	-	0.14	0.14	0.14	0.14
95% Lilliefors Critical Value	-	0.09	0.09	0.09	0.09
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	-	86.00	76.44	62.64	97.68
5% Upper	-	124.52	121.52	94.48	121.12
95% Lower	-	174.24	170.68	155.44	164.64
95% Upper	-	198.84	198.68	178.28	209.72

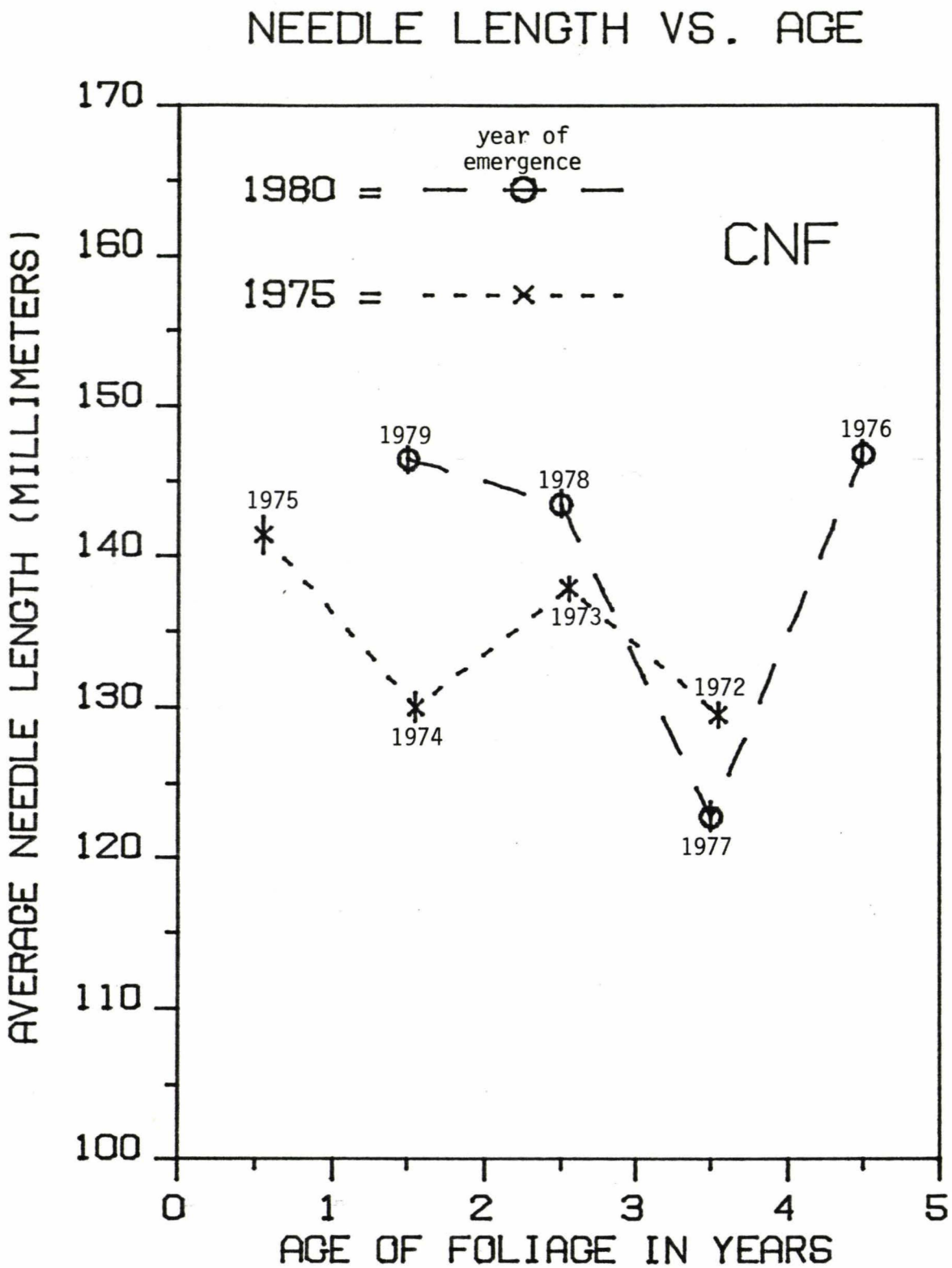

Figure 20. Average ponderosa pine needle length at all CNF sites, 1975 and 1980 collections.

Table 37

Comparisons of Needle Length in 1975 and 1980 Collections Over Custer National Forest Sites
Three-Factor ANOVA with Repeated Measures on Collection and Age of Foliage

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Value	Probability of Occurrence
Between Trees					
Site (S)	50,100	9	5,566	4.68	<0.0001
Error	102,227	86	1,188		
Within Trees					
Collection (C)	3,401	1	3,401	21.44	<0.0001
CxS	2,945	9	327	2.06	0.0418
Error	13,646	86	158		
Age (A)	20,568	2	10,284	74.01	<0.0001
AxS	10,112	18	561	4.04	<0.0001
Error	23,902	172	138		
CxA	14,097	2	7,048	49.70	<0.0001
CxAxS	9,530	18	529	3.73	<0.0001
Error	24,392	172	141		

Table 38

AVERAGE DRY WEIGHT OF ONE NEEDLE (MILLIGRAMS)
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1975 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	49	124	123	122	0
Maximum Value	136.40	132.40	138.80	169.20	-
Minimum Value	28.00	30.00	42.00	39.60	-
Average	74.87	69.93	84.39	82.99	-
Variance	467.24	424.63	378.36	502.38	-
Standard Deviation	21.62	20.61	19.45	22.41	-
Standard Error of Mean	3.09	1.85	1.75	2.03	-
Width of 95% Confidence Limit	6.21	3.66	3.47	4.02	-
Sample Precision	8.30	5.24	4.11	4.84	-
5% Quantile	42.40	40.00	49.20	48.80	-
25% Quantile	59.20	54.60	73.20	68.00	-
50% Quantile (Median)	75.60	68.60	82.80	79.20	-
75% Quantile	87.60	81.40	98.00	97.20	-
95% Quantile	105.60	109.60	114.00	120.00	-
Coefficient of Dispersion	6.24	6.07	4.48	6.05	-
Coefficient of Variation	28.87	29.47	23.05	27.01	-
Skewness	0.27	0.46	0.21	0.70	-
Standard Error	0.34	0.22	0.22	0.22	-
Width of 95% Confidence Limit	0.67	0.43	0.43	0.43	-
Probability of Occurrence (%)	43.37	3.38	32.82	0.15	-
Kurtosis	0.36	0.05	0.25	0.99	-
Standard Error	0.67	0.43	0.43	0.43	-
Width of 95% Confidence Limit	1.31	0.85	0.85	0.85	-
Probability of Occurrence (%)	59.03	90.99	56.11	2.25	-
Kolmogorov-Smirnov Maximum	0.07	0.07	0.06	0.10	-
95% K-S Critical Value	0.19	0.12	0.12	0.12	-
95% Lilliefors Critical Value	0.13	0.08	0.08	0.08	-
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	28.00	31.60	43.20	39.60	-
5% Upper	49.60	45.20	57.20	53.60	-
95% Lower	99.20	102.40	111.60	116.40	-
95% Upper	136.40	117.20	137.60	139.60	-

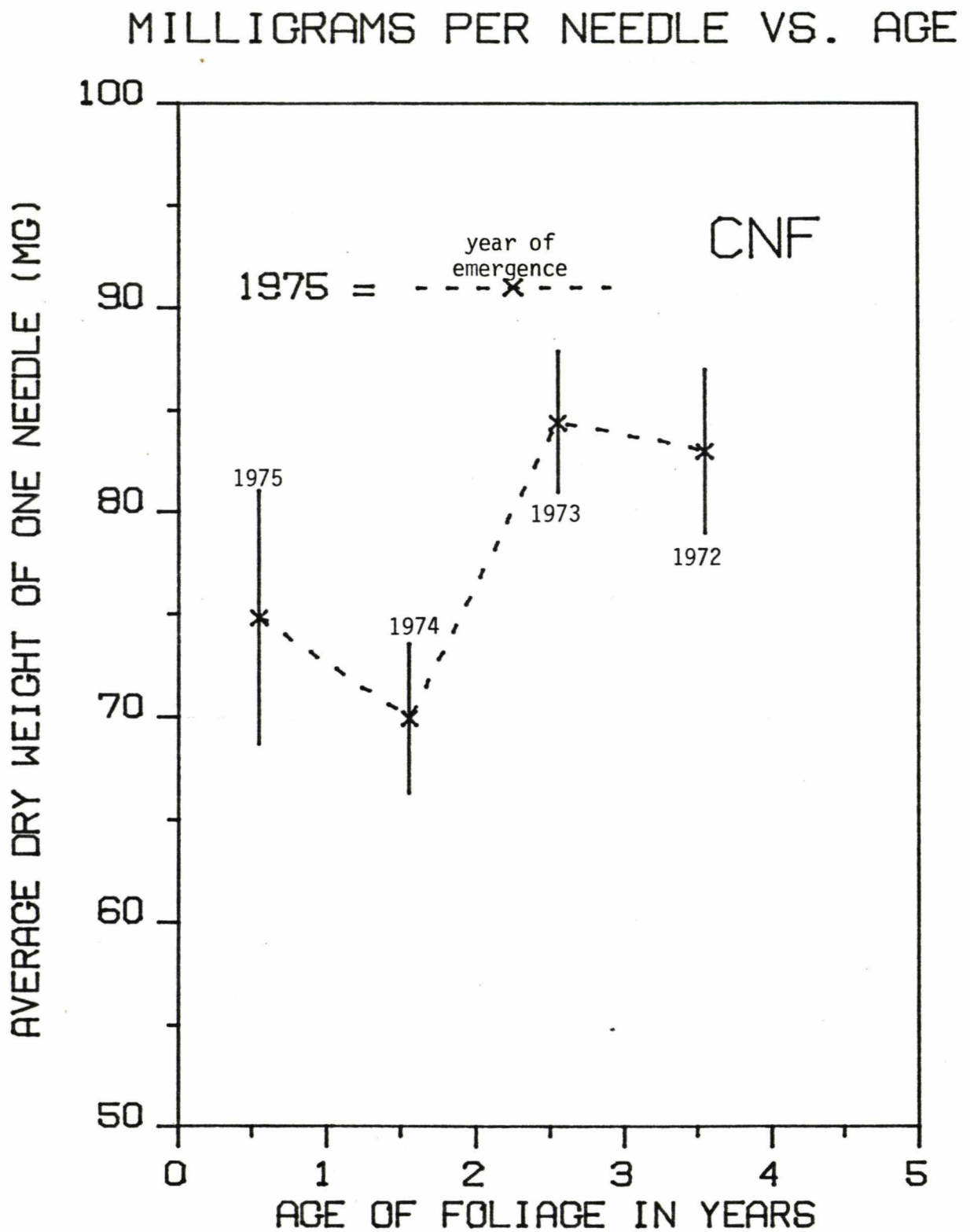

Figure 21. Average dry weight of one ponderosa pine needle at all CNF sites, 1975 collection.

Cross Sectional Area

Just as the average needle weight and length fluctuate each year, so too does the average cross sectional area of a needle fascicle. Table 39 presents the data on the cross sectional areas collected in 1975. It can be seen in this table that the average cross sectional area of a needle fascicle was 2.3 mm^2, with the needles that emerged in 1973 having the greatest cross sectional area (2.43 mm^2) and the needles that emerged in 1974 having the least cross sectional area (2.18 mm^2). Figure 22 graphs this data, and the similarity of this figure to that portraying the average dry weight (Figure 21) is readily apparent.

Moisture Content

Table 40 presents the moisture content data collected in 1975. As shown, the moisture content of pine needles falls with increasing age of foliage. The needles in the first year of growth had the highest moisture content (54% water), while the fourth-year needles had the lowest moisture content (48% water). These data are graphed in Figure 23 and demonstrate the continuous decrease in moisture content with increasing age of foliage.

Characterization of the Baseline Distributions of Tip Burn and Mottling

Characterization of the baseline distributions of the frequency of occurrence of tip burn and mottling serve three useful purposes. First, knowledge of the underlying distribution of a random variable facilitates the statistical analysis of the variable by allowing the distribution to be completely specified by its characteristic parameters (i.e., mean and standard deviations in the case of a Gaussian distribution or a mean only in the case of a Poisson distribution). Second, the distributions of derivative statistics can be determined. Third, knowledge of a variable's distribution

Table 39

AVERAGE CROSS SECTIONAL AREA OF NEEDLE BUNDLE (SQUARE MILLIMETERS)
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1975 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	60	130	130	129	0
Maximum Value	4.54	3.93	5.58	5.05	-
Minimum Value	0.96	0.86	0.92	0.93	-
Average	2.22	2.18	2.43	2.39	-
Variance	0.55	0.34	0.52	0.52	-
Standard Deviation	0.74	0.58	0.72	0.72	-
Standard Error of Mean	0.10	0.05	0.06	0.06	-
Width of 95% Confidence Limit	0.19	0.10	0.13	0.13	-
Sample Precision	8.62	4.65	5.15	5.27	-
5% Quantile	1.13	1.34	1.43	1.40	-
25% Quantile	1.61	1.77	1.88	1.83	-
50% Quantile (Median)	2.13	2.14	2.33	2.30	-
75% Quantile	2.77	2.53	2.88	2.75	-
95% Quantile	3.37	3.22	3.81	3.69	-
Coefficient of Dispersion	0.25	0.16	0.21	0.22	-
Coefficient of Variation	33.34	26.80	29.70	30.27	-
Skewness	0.60	0.58	0.95	0.76	-
Standard Error	0.31	0.21	0.21	0.21	-
Width of 95% Confidence Limit	0.61	0.42	0.42	0.42	-
Probability of Occurrence (%)	5.35	0.61	0.00	0.03	-
Kurtosis	0.47	0.43	2.14	0.83	-
Standard Error	0.61	0.42	0.42	0.42	-
Width of 95% Confidence Limit	1.19	0.83	0.83	0.83	-
Probability of Occurrence (%)	44.44	31.25	0.00	4.91	-
Kolmogorov-Smirnov Maximum	0.08	0.06	0.07	0.07	-
95% K-S Critical Value	0.17	0.12	0.12	0.12	-
95% Lilliefors Critical Value	0.11	0.08	0.08	0.08	-
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	0.96	1.05	1.04	1.16	-
5% Upper	1.31	1.46	1.65	1.48	-
95% Lower	3.12	3.00	3.37	3.39	-
95% Upper	4.54	3.87	4.47	4.31	-

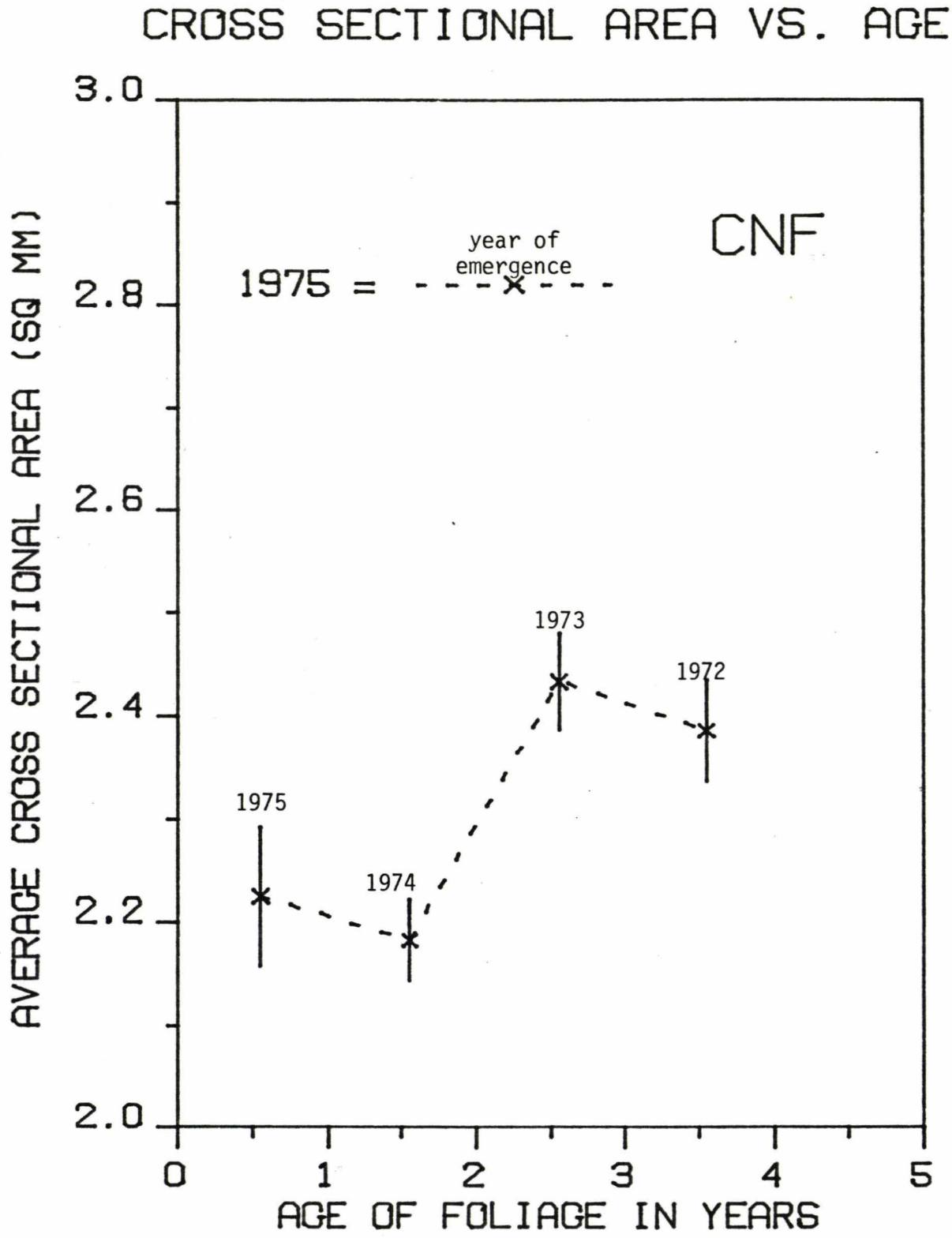

Figure 22. Average cross sectional area of ponderosa pine needle bundle at all CNF sites, 1975 collection.

Table 40

AVERAGE MOISTURE CONTENT OF PINE NEEDLES (PERCENT WATER)
ALL CUSTER NATIONAL FOREST SITES COMBINED, 1975 COLLECTION

	Year of Foliage				
	First	Second	Third	Fourth	Fifth
Sample Size	49	124	123	121	0
Maximum Value	61.01	76.87	60.77	68.71	-
Minimum Value	41.65	26.86	28.52	26.09	-
Average	54.31	49.98	49.50	47.75	-
Variance	13.55	27.48	15.96	30.73	-
Standard Deviation	3.68	5.24	4.00	5.54	-
Standard Error of Mean	0.53	0.47	0.36	0.50	-
Width of 95% Confidence Limit	1.06	0.93	0.71	1.00	-
Sample Precision	1.95	1.86	1.44	2.09	-
5% Quantile	47.97	41.83	44.44	41.52	-
25% Quantile	52.83	47.81	46.85	45.33	-
50% Quantile (Median)	54.55	50.00	49.82	47.79	-
75% Quantile	56.44	52.51	51.78	50.00	-
95% Quantile	59.65	55.98	56.03	54.91	-
Coefficient of Dispersion	0.25	0.55	0.32	0.64	-
Coefficient of Variation	6.78	10.49	8.07	11.61	-
Skewness	-0.90	-0.06	-0.85	0.24	-
Standard Error	0.34	0.22	0.22	0.22	-
Width of 95% Confidence Limit	0.67	0.43	0.43	0.43	-
Probability of Occurrence (%)	0.84	78.04	0.01	27.38	-
Kurtosis	1.94	8.61	5.55	5.37	-
Standard Error	0.67	0.43	0.43	0.44	-
Width of 95% Confidence Limit	1.31	0.85	0.85	0.86	-
Probability of Occurrence (%)	0.36	0.00	0.00	0.00	-
Kolmogorov-Smirnov Maximum	0.09	0.14	0.05	0.15	-
95% K-S Critical Value	0.19	0.12	0.12	0.12	-
95% Lilliefors Critical Value	0.13	0.08	0.08	0.08	-
95% Confidence Limits of Selected Quantiles					
Quantile Limit					
5% Lower	41.65	33.21	42.05	27.68	-
5% Upper	49.29	46.02	44.83	42.01	-
95% Lower	58.77	55.09	54.08	52.76	-
95% Upper	61.01	61.99	60.06	66.85	-

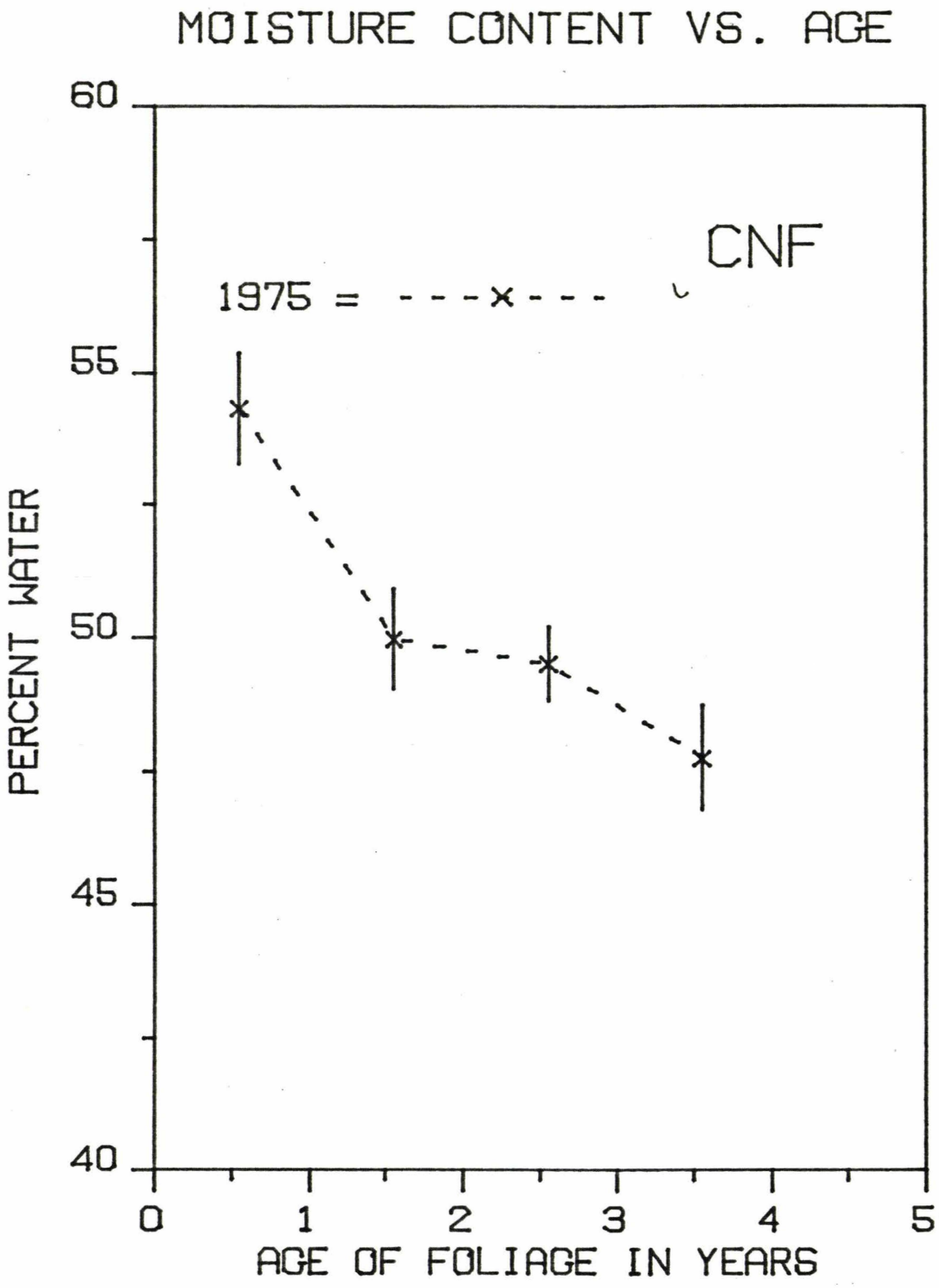

Figure 23. Average moisture content of ponderosa pine needles at all CNF sites, 1975 collection.

allows a suitable transformation of the data to be made and, if necessary, to remove any dependency of the variance on the mean or other feature of the data that interferes with a particular parametric statistical test to be performed.

In an effort to obtain as accurate and precise a representation of the baseline conditions existing on the Custer National Forest as possible, the 1975 and 1976 data were pooled, thereby doubling the number of samples available for analysis. Figure 24 shows the manner in which the mean frequency of occurrence of tip burn varies with increasing age of foliage. This figure is similar to Figure 4, which portrays only the 1975 data. These figures show the rate at which the frequency of occurrence of tip burn increases throughout the lifetime of a needle.

Figure 25 shows the relative cumulative frequency distributions of the occurrence of tip burn for each age of foliage. As suggested by this figure, which plots the proportion of all needles with tip burn on a logarithmic axis, the data can be considered, as a first approximation, to be log-normally distributed. Examination of the skewness and kutosis indicate, however, that while the log-normal fit is better than a linear-normal fit, the data are not log-normally distributed.

Figure 25 also indicates that less than 0.2% of the first-year needles were affected by tip burn and that less than 10% of the fourth-year needles were affected. Since 100 needles were examined for the various pathologies, the number of tip burned needles present in the 100 needles examined can be considered to be the number of times a rare event occurs in a given sampling. The number of occurrences of a rare event in a sample of a given size follows the Poisson distribution.

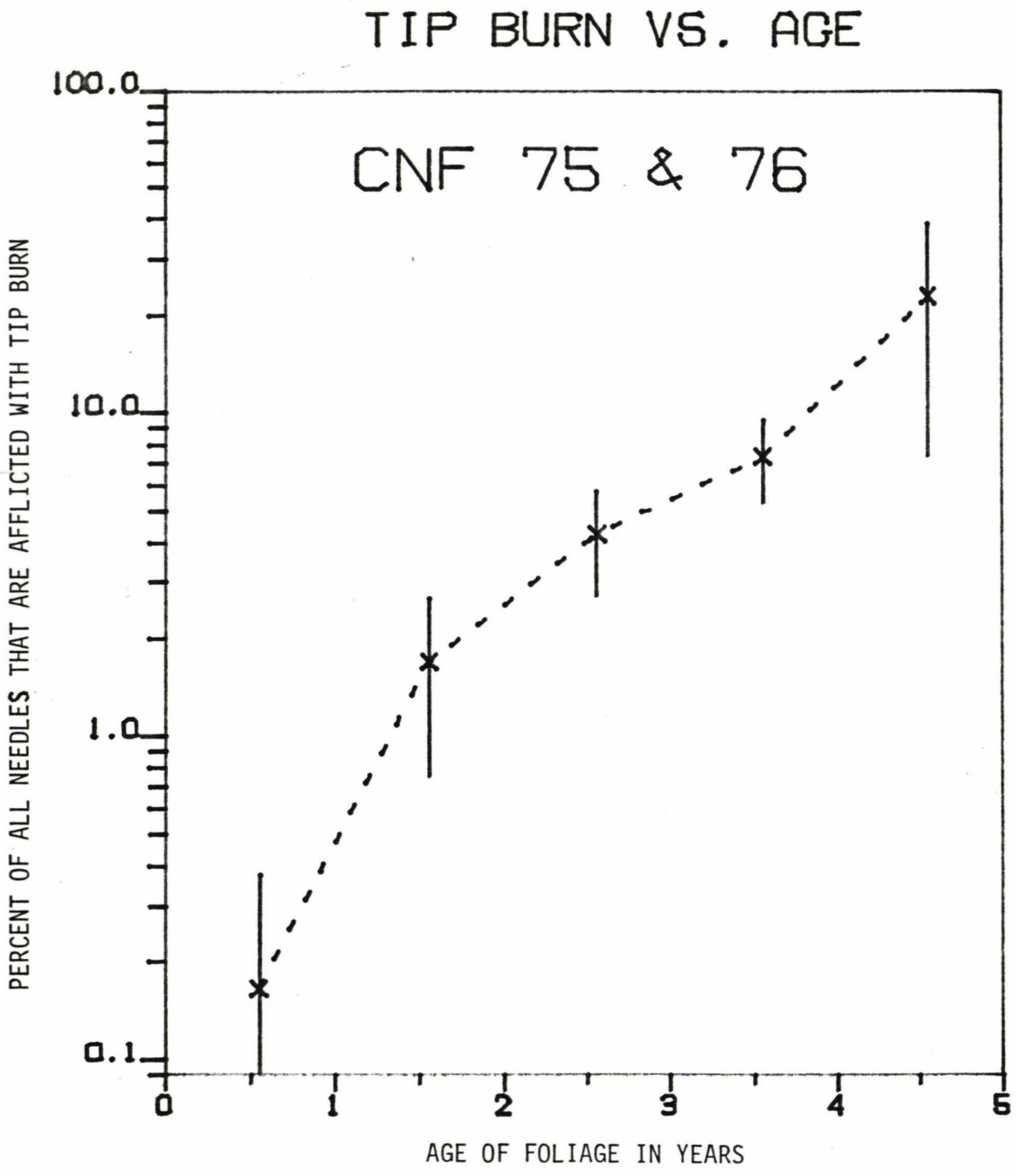

Figure 24. Percent of all ponderosa pine needles afflicted with tip burn at all CNF sites, 1975 and 1976 collections.

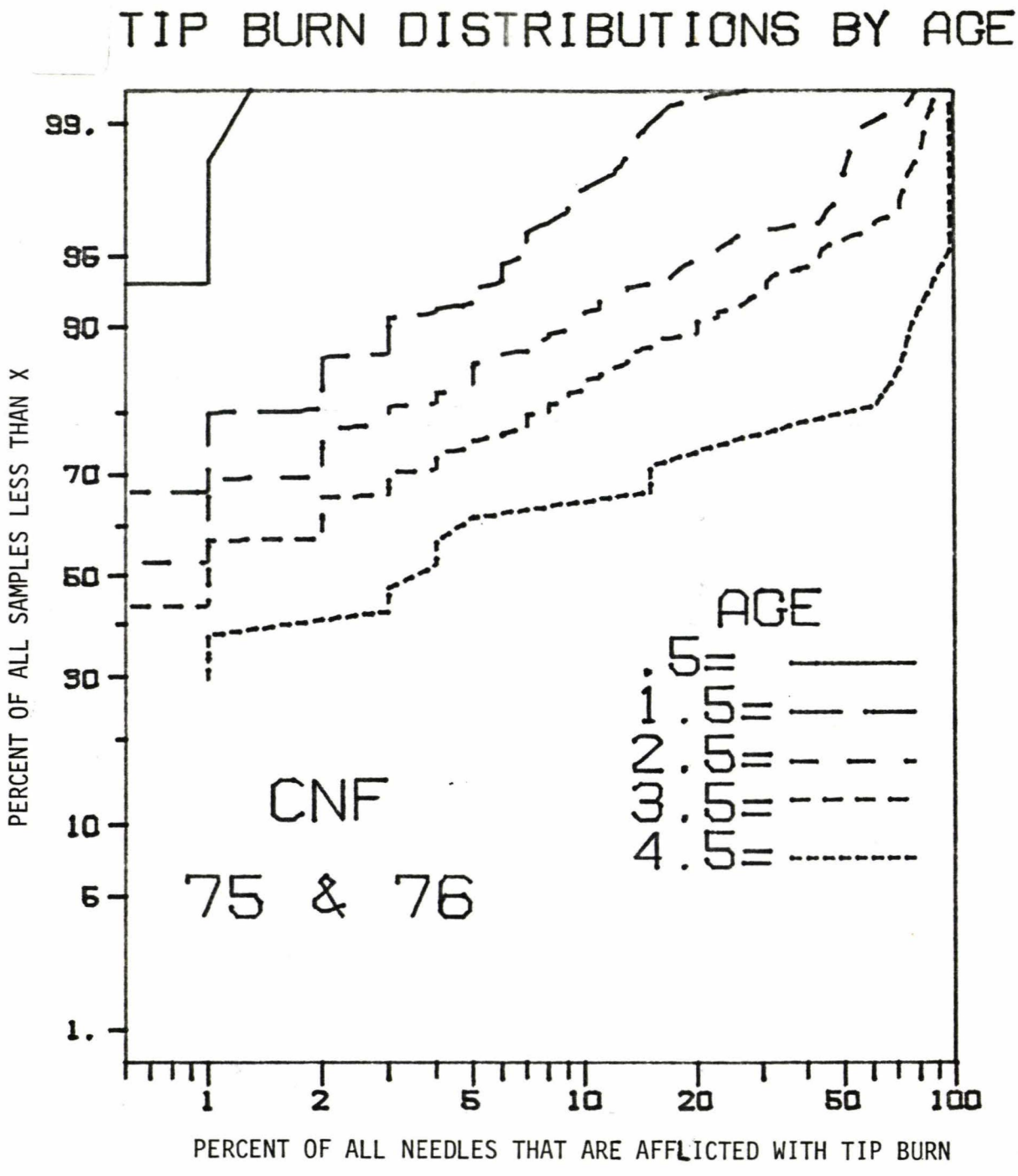

Figure 25. Relative cumulative frequency distributions of the percent of all ponderosa pine needles afflicted with tip burn at all CNF sites, 1975 and 1976 collections.

The negative binomial distribution describes the nature of the expected results from a sampling of randomly varying Poisson populations. If each tree has a slightly different proportion of tip burned needles, then the result of sampling a number of trees or sites should follow the negative binomial distribution. The negative binomial distribution is completely specified by its mean and a parameter, k, which is often a constant for a particular biological variable being sampled.

Figures 26 through 30 show histograms of the tip burn levels in the first through fifth years of growth, respectively. Superimposed upon these histograms is a negative binomial fit to the data. It can be seen from these figures that the negative binomial is a reasonably good fit to the data, with k rising from 0.07 in the first year to 0.31 in the fifth year of growth and relatively little change in k between the second and fourth years of growth (0.16 to 0.22). The second through fourth years of growth have a common k of 0.15.

Mottling was seen to behave differently from tip burn in 1975 (Figures 4 and 7), and the 1975 and 1976 data are very similar to the 1975, indicating that no major changes occurred in the patterns of mottling in 1976. Figure 31 shows the levels of mottling with increasing age of needles. It can be seen that the proportion of mottled needles rises most rapidly for the first two years and then levels off.

Figure 32 shows the relative cumulative frequency distribution for the occurrence of mottling by age of foliage. The similar nature of the second through fifth years of foliage is readily apparent. Once again, because the levels of mottling are low, the number of mottled needles present in a sample should follow a Poisson distribution. If each tree has a different proportion of mottled needles, then the negative binomial will describe the results of sampling many trees.

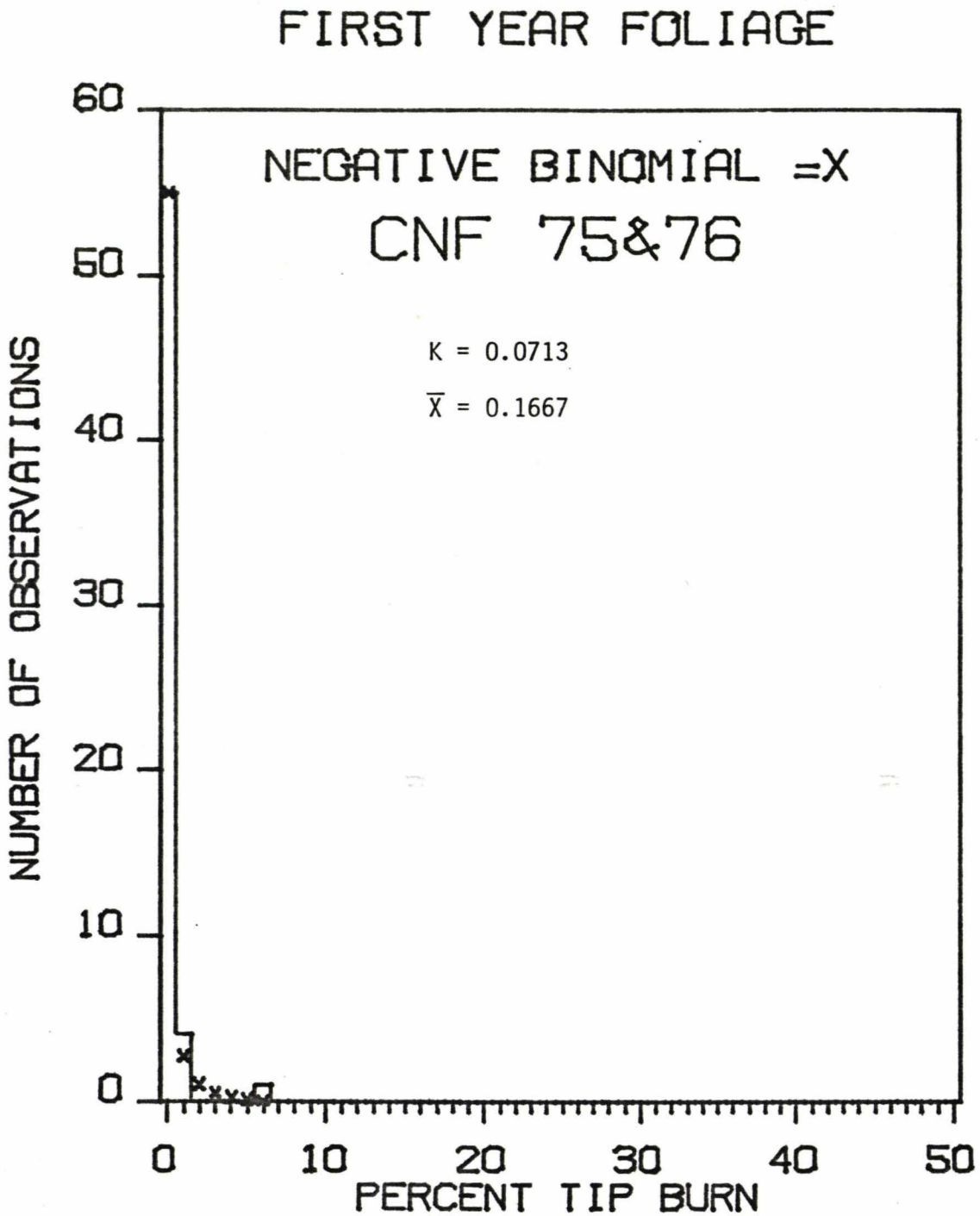

Figure 26. Histogram of the percent of first year ponderosa pine needles afflicted with tip burn at all CNF sites, 1975 and 1976 collections.

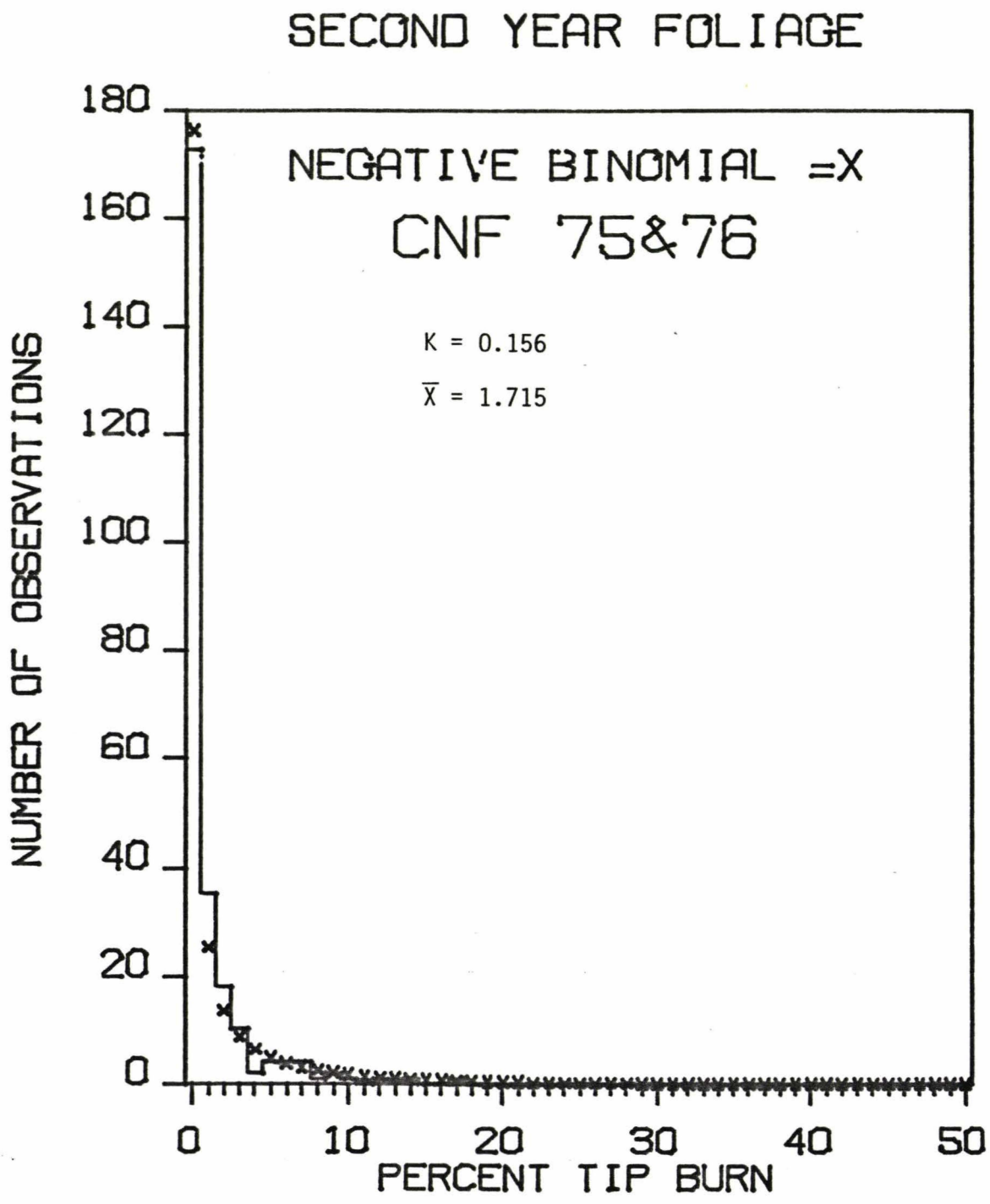

Figure 27. Histogram of the percent of second year ponderosa pine needles afflicted with tip burn at all CNF sites, 1975 and 1976 collections.

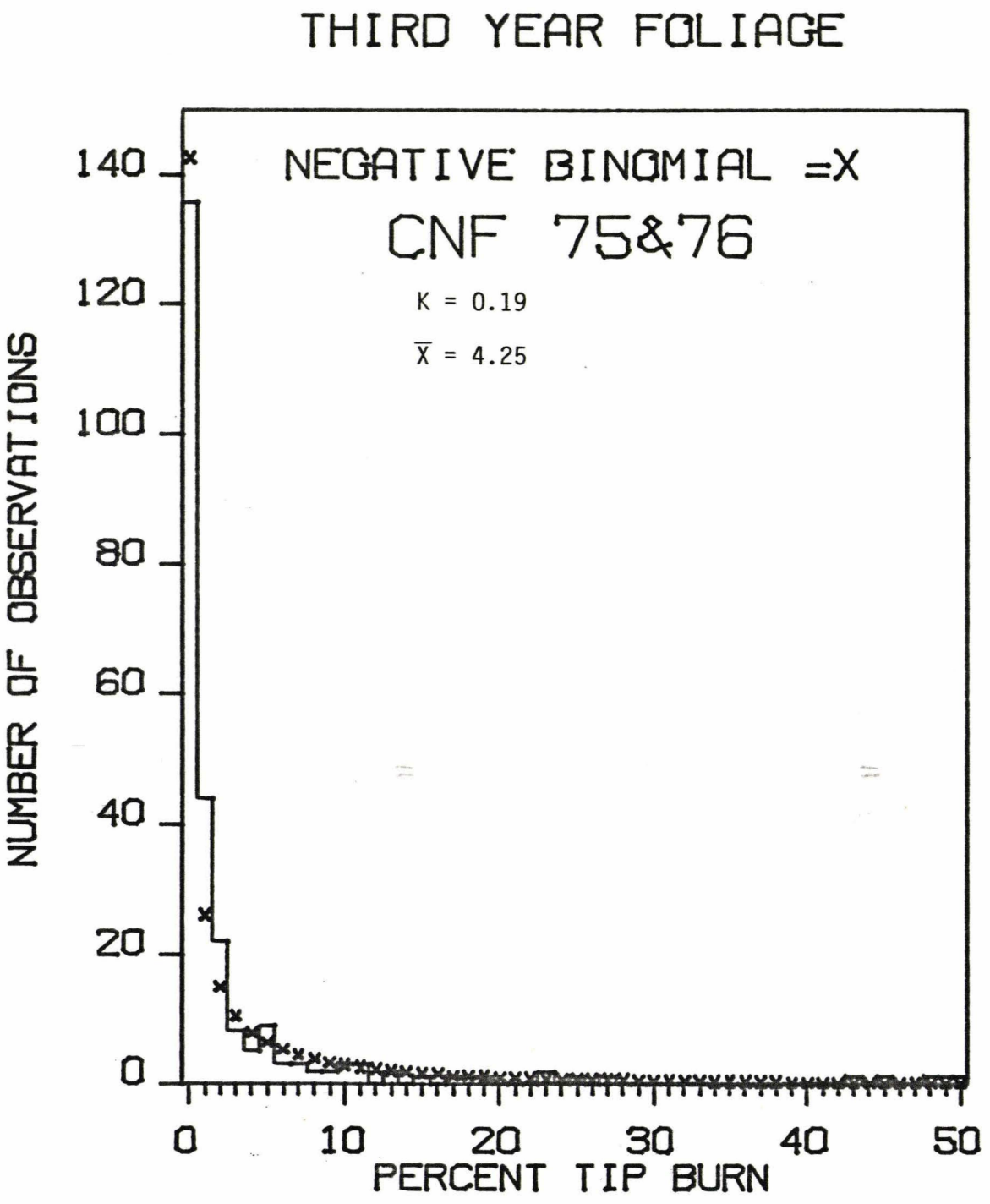

Figure 28. Histogram of the percent of third year ponderosa pine needles afflicted with tip burn at all CNF sites, 1975 and 1976 collections.

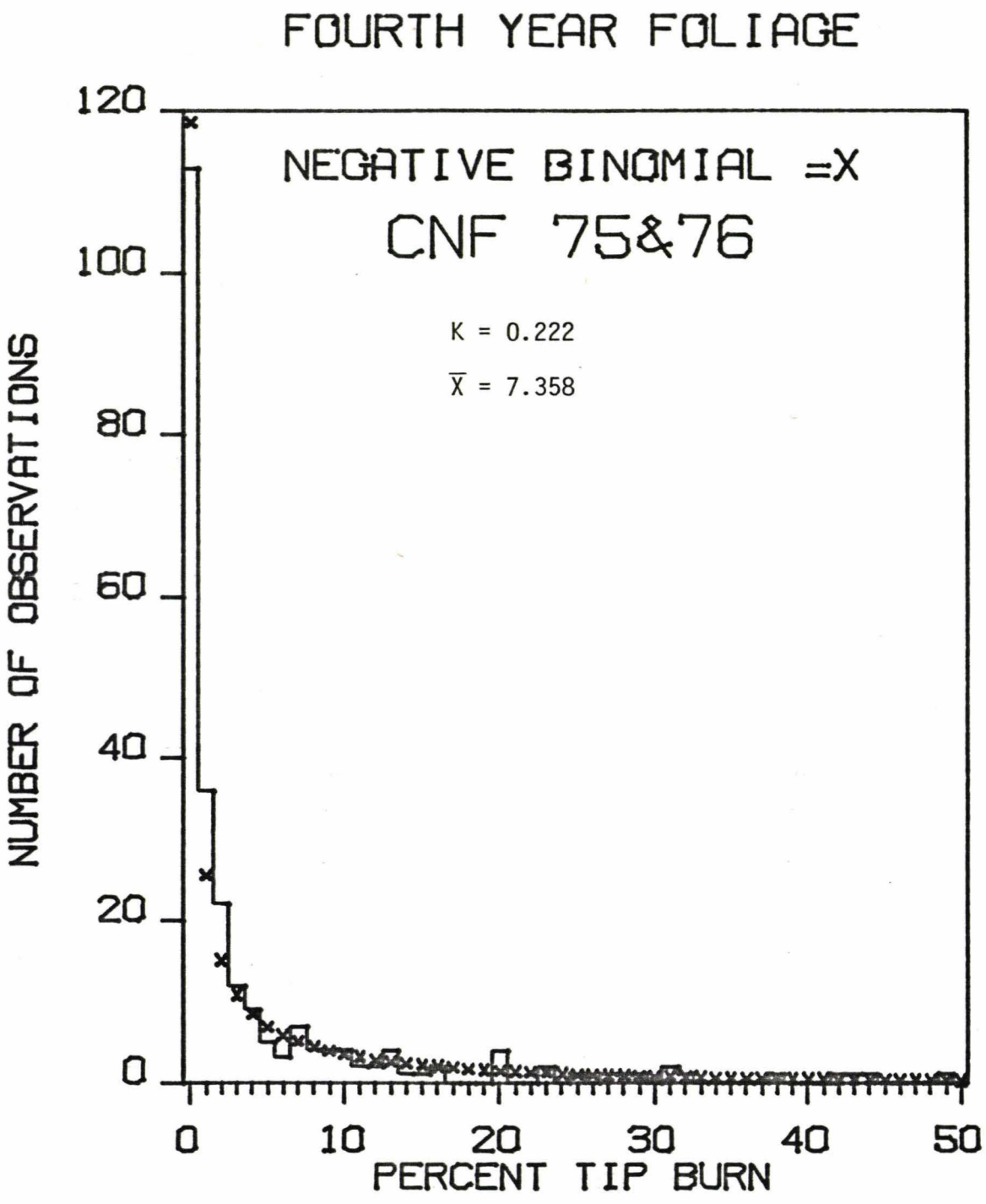

Figure 29. Histogram of the percent of fourth year ponderosa pine needles afflicted with tip burn at all CNF sites, 1975 and 1976 collections.

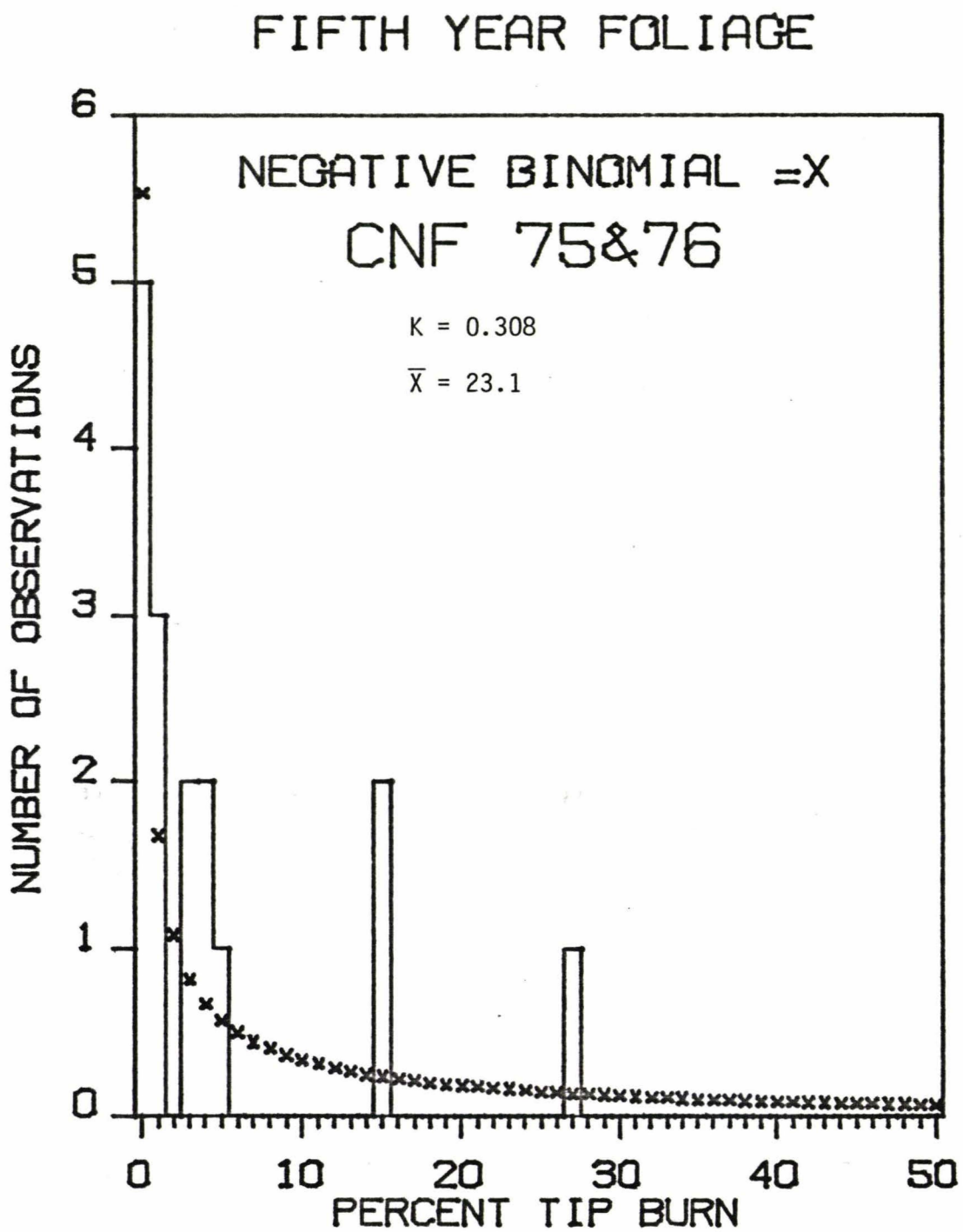

Figure 30. Histogram of the percent of fifth year ponderosa pine needles afflicted with tip burn at all CNF sites, 1975 and 1976 collections.

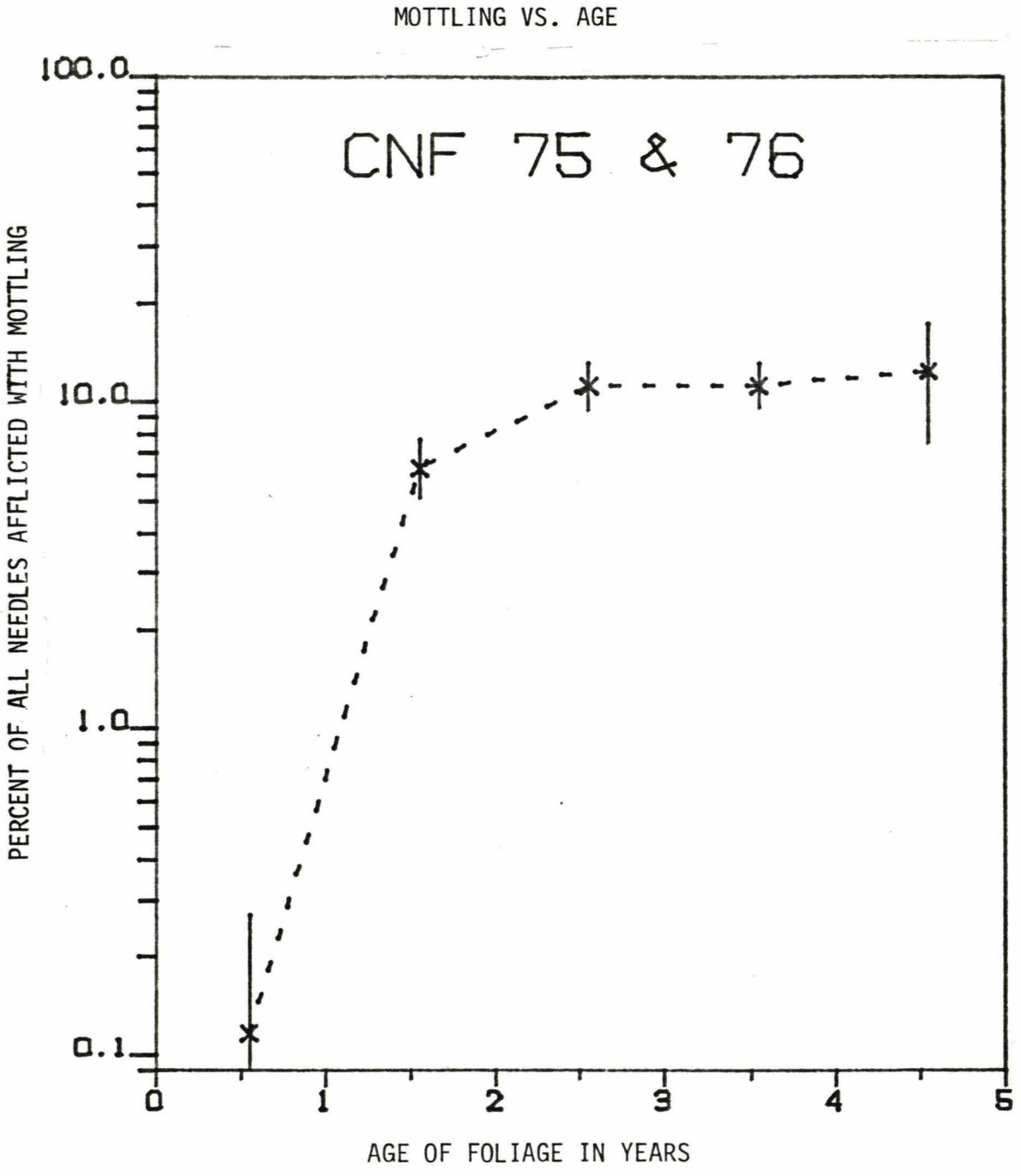

Figure 31. Percent of ponderosa pine needles afflicted with mottling at all CNF sites, 1975 and 1976 collections.

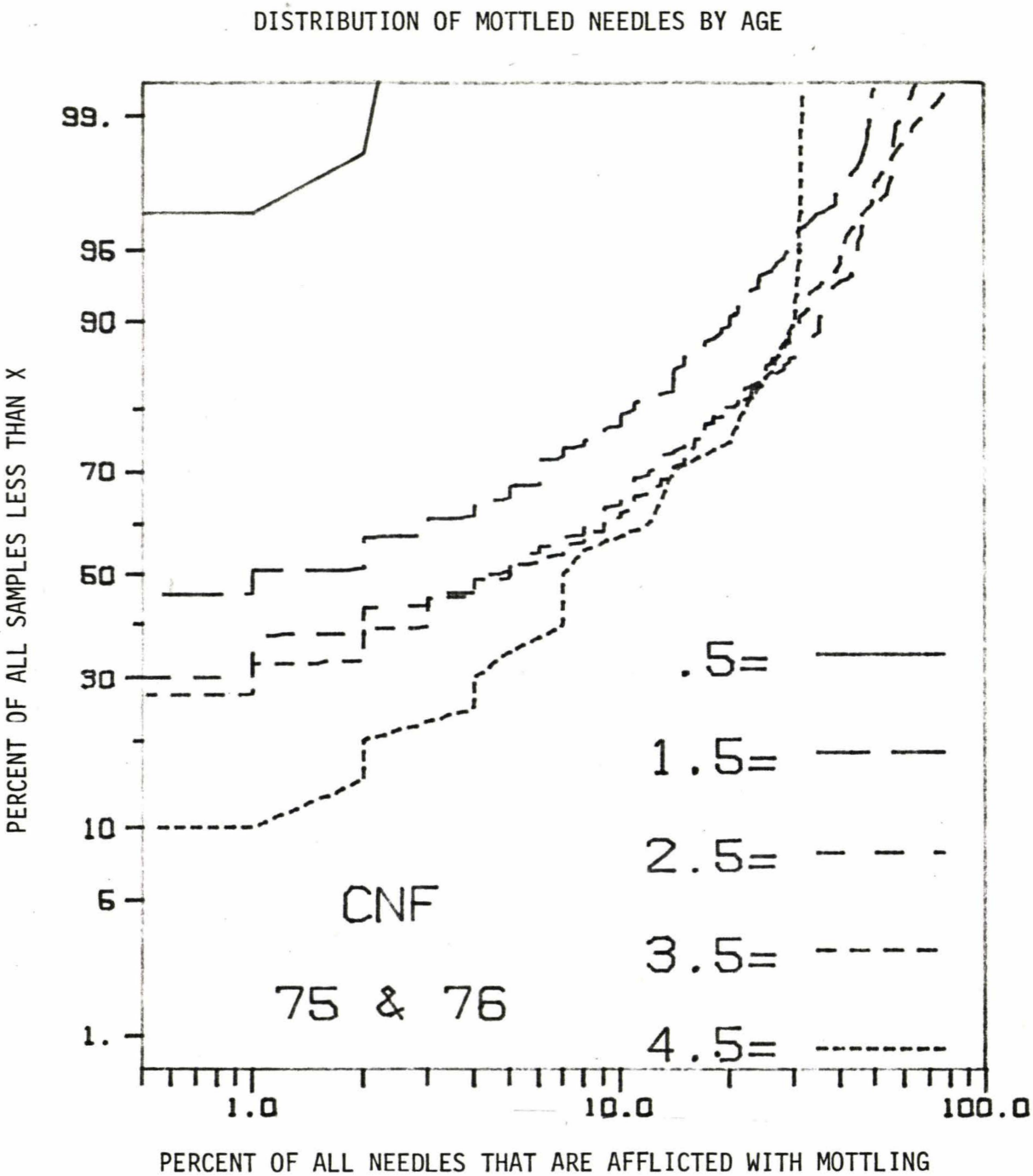

Figure 32. Relative cumulative frequency distributions of the percent of all ponderosa pine needles afflicted with mottling at all CNF sites, 1975 and 1976 collections.

Figures 33 through 37 present the histograms of the frequency of occurrence of mottling for each year of foliage for the 1975 and 1976 collections. Superimposed upon each of these histograms is a negative binomial fit to the data. These figures show that the k rises from 0.0354 in the first year of growth to 1.25 for the fifth year of growth. However, very little change is seen in the second through fourth years of foliage, the years for which the greatest sample size is available (260 for the second through fourth years of growth vs. 60 for the first and fifth years of growth). The common k for the second through fourth years of growth was determined to be 0.52.

Because the baseline distributions of tip burn and mottling can be described as negative binomials with characteristic k's, the technique of sequential sampling can be employed to efficiently determine whether the proportion of needles with these pathologies exceeds some level judged to be of biological importance. In this type of sampling, only enough samples must be taken to characterize the observed proportions of a pathology as being greater or less than the predetermined level. Sequential sampling is most useful when very low or very high proportions of a pathology are present, as a decision will be quickly reached. The computational details of this procedure, including formula for determining the average number of trees needed to categorize the levels of the various pathologies can be found in various texts on biological sampling (for example, see Southwood, 1981, pp. 46 ff) and reports of actual experiments (Oakland, 1950).

For example, if it was desired to determine whether the frequency of occurrence of tip burn was less than 5% or greater than 25% in an area, then using the equations presented in Southwood, it is possible to determine when sufficient trees have been sampled to be able to specify, with a given

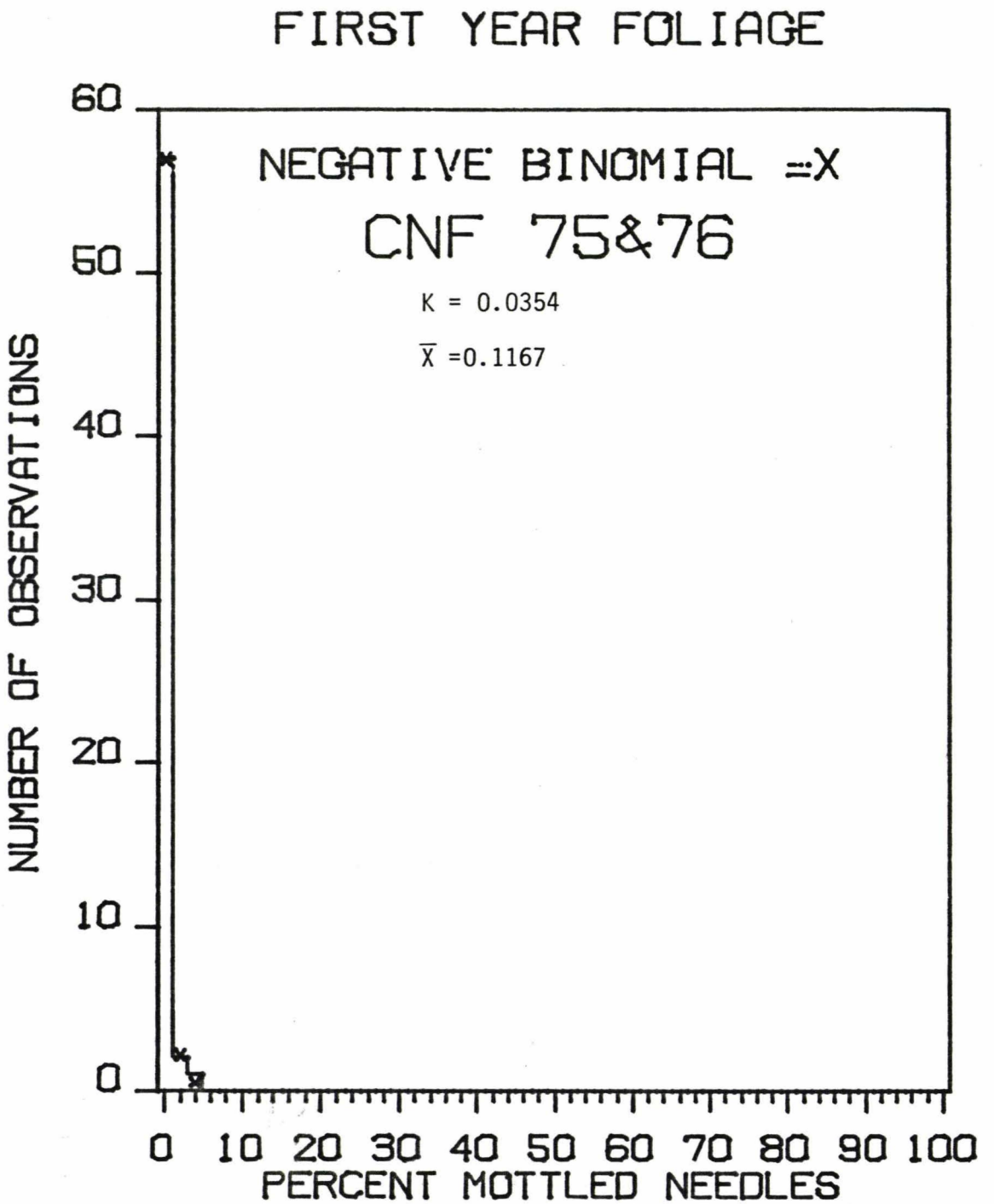

Figure 33. Histogram of the percent of first year ponderosa pine needles afflicted with mottling at all CNF sites, 1975 and 1976 collections.

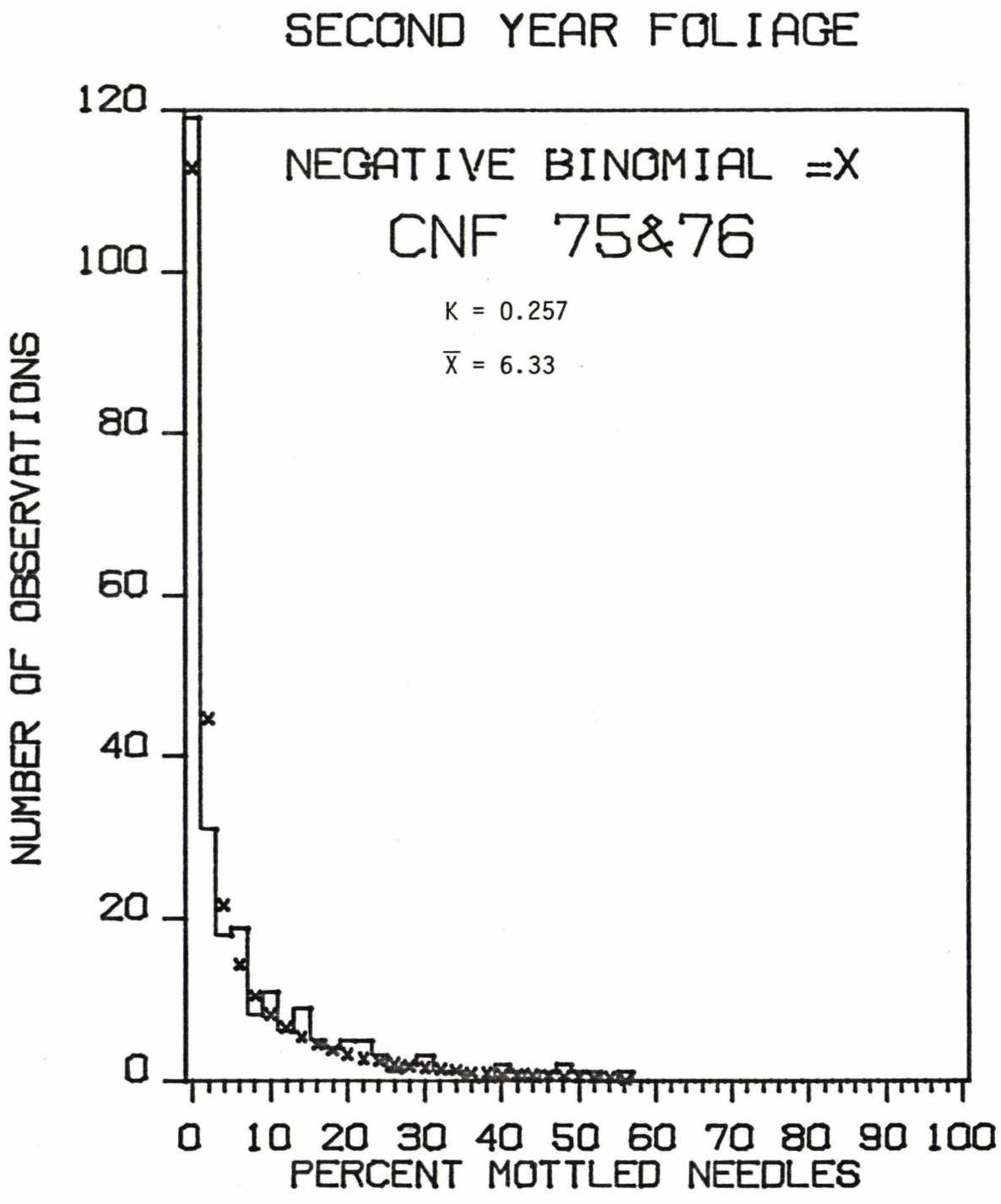

Figure 34. Histogram of the percent of second year ponderosa pine needles afflicted with mottling at all CNF sites, 1975 and 1976 collections.

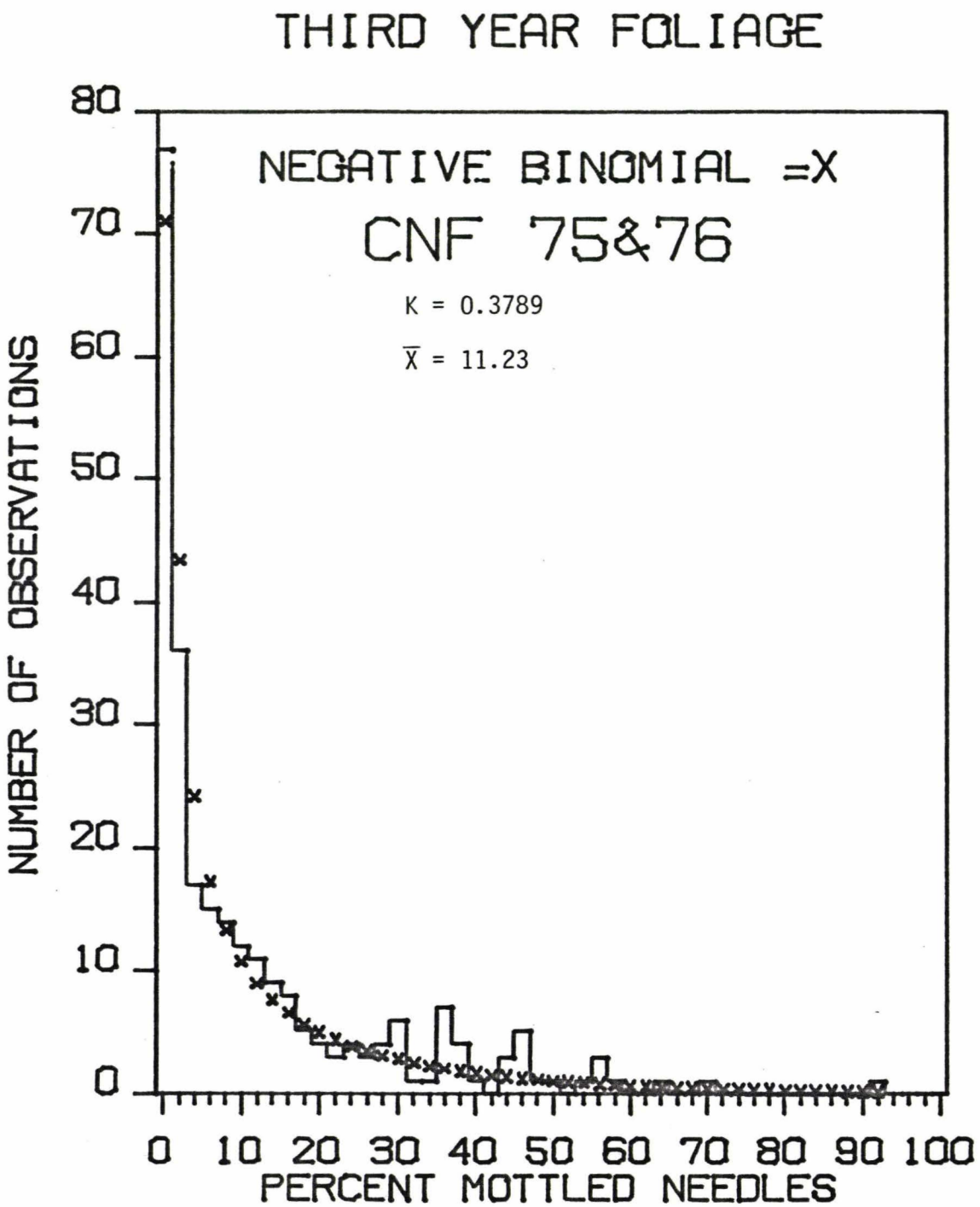

Figure 35. Histogram of the percent of third year ponderosa pine needles afflicted with mottling at all CNF sites, 1975 and 1976 collections.

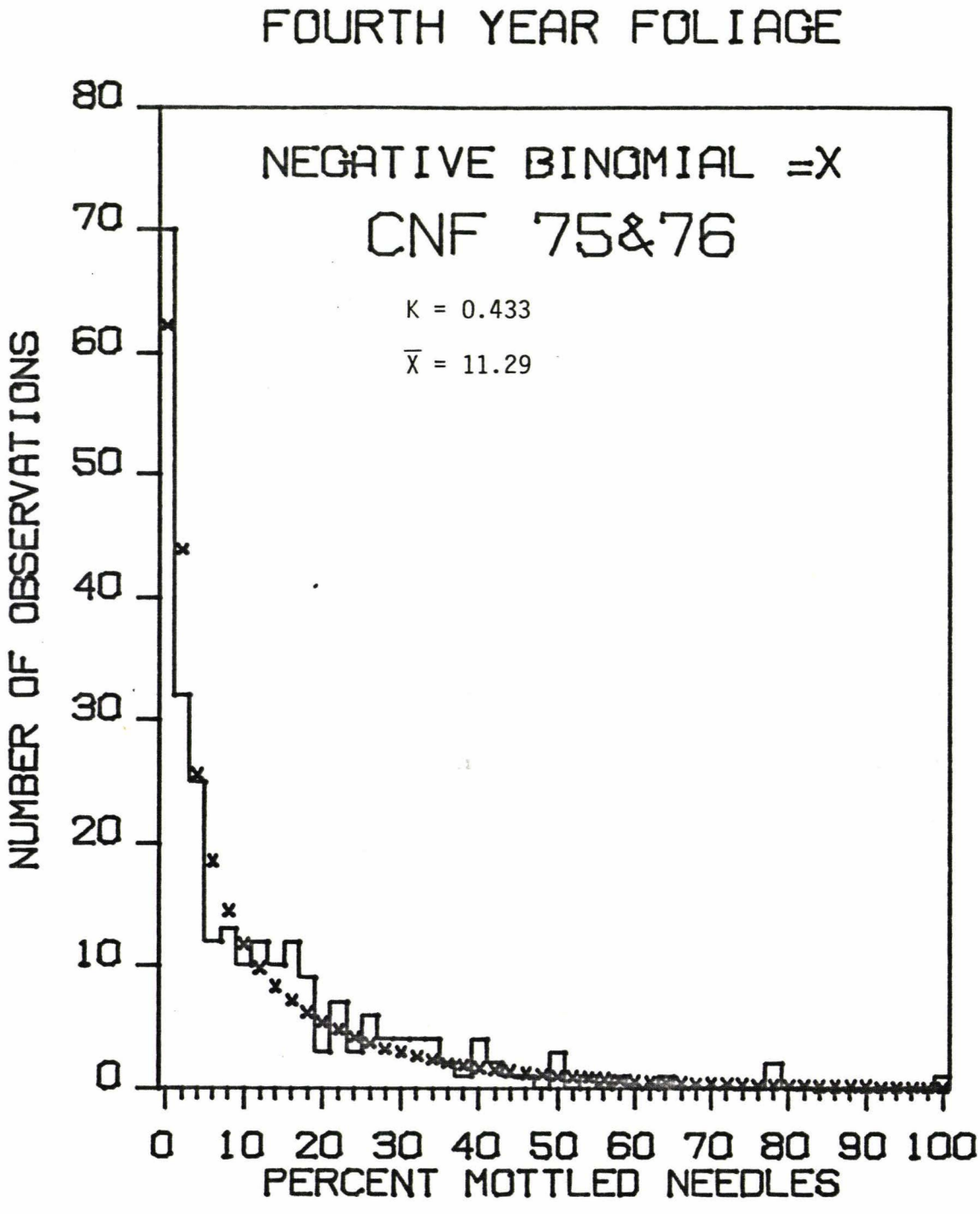

Figure 36. Histogram of the percent of fourth year ponderosa pine needles afflicted with mottling at all CNF sites, 1975 and 1976 collections.

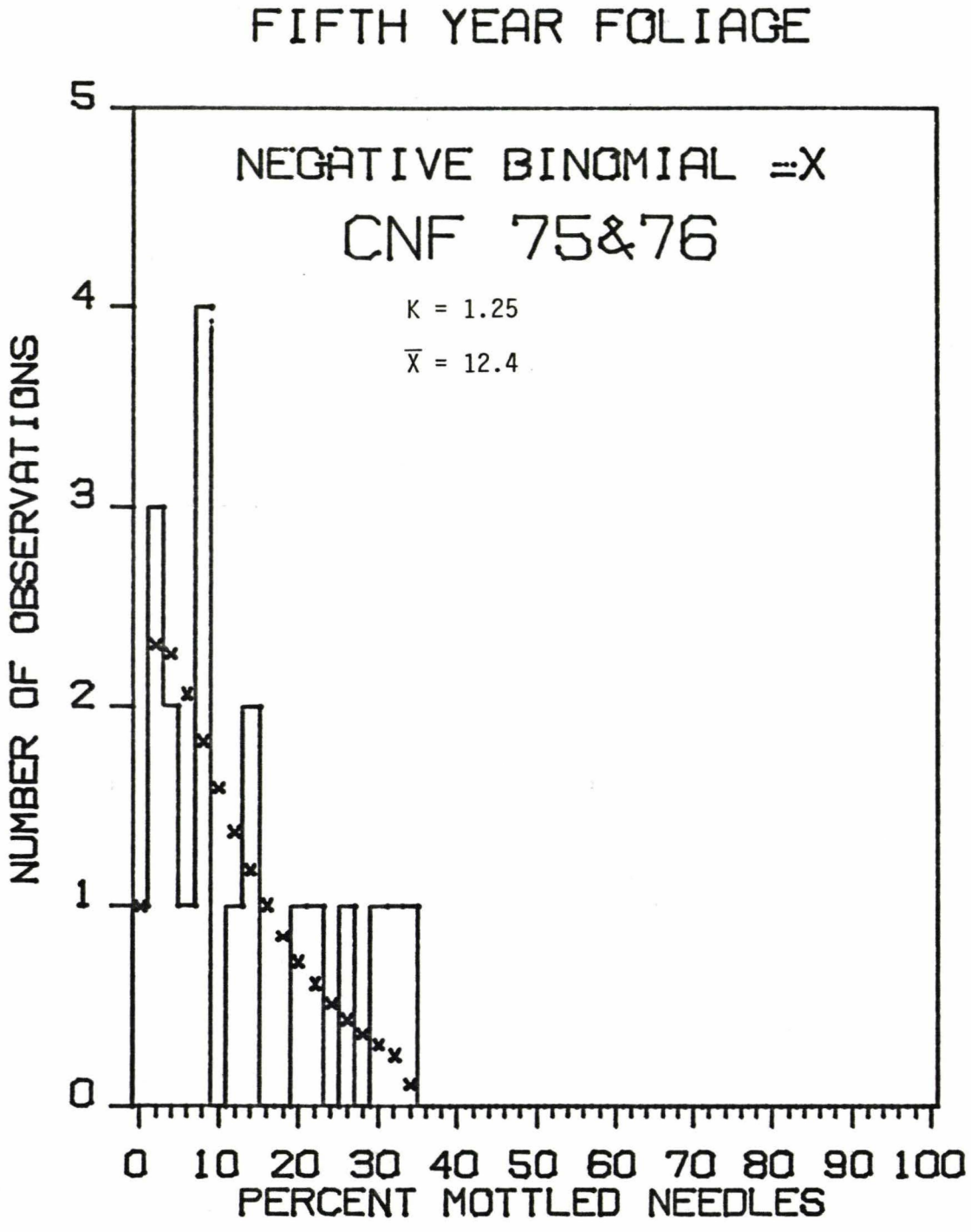

Figure 37. Histogram of the percent of fifth year ponderosa pine needles afflicted with mottling at all CNF sites, 1975 and 1976 collections.

probability of error, which category the area is in. The equations given in Southwood are:

$$d_o = \theta n + h_o$$

and

$$d_1 = \theta n - h_1$$

where:

d = cumulative number of tip burned needles observed

$$\theta = k \cdot \frac{\log(p_1/q_o)}{\log \frac{p_1 q_o}{p_o q_1}}$$

$$p = \frac{\bar{x}}{k}$$

$$q = 1 + p$$

$$h_o = \frac{\log \frac{\beta}{1-\alpha}}{\log \frac{p_1 q_o}{p_o q_1}}$$

$$h_1 = \frac{\log \frac{1-\beta}{\alpha}}{\log \frac{p_1 q_o}{p_o q_1}}$$

α = probability of making type I error

β = probability of making type II error

Substituting the observed value of k in this equation (0.15) and setting $\alpha = \beta = .05$, the following critical regions are delineated:

$$d_{crit} = 10 \cdot \text{number of trees} \pm 125$$

This means that if, after sampling 25 trees, 125 tip burned needles are observed, then the forest has 5% or less of all needles tip burned. Similarly, if after sampling 25 trees, 375 or more tip burned needles are found, then at least 25% of all the needles in the forest are tip burned.

Comparison of CNF Sites and Billings Site GB 1

By measuring the foliar characteristics of a ponderosa pine stand known to be in an area subject to chronic fumigations by a coal-fired power plant, the sensitivity of the variables studied (fluoride, sulfur, etc.) as indicators of pollution can be determined. Figure 38 contrasts the foliar levels of fluoride found on the CNF sites in 1975 and 1976 with the corresponding levels found on the Billings site, GB 1, in 1976 and 1977. As shown, the fluoride levels are elevated at Billings relative to the Custer National Forest. Whereas fluoride levels were 1 ppm and 3 ppm on the Custer National Forest in 1975 and 1980, respectively, the levels at Billings are seen to rise from 5 ppm in the first year of growth to 65 ppm in the fifth year of foliage. Reference to Appendix A, Figure A-21, will indicate that the levels of fluoride in the foliage at Billings fell between 1976-77 and 1980 from a mean of 50 ppm to 20 ppm, although they are still greater than those that exist on the Custer National Forest, either in 1975 or 1980.

Figure 39 portrays the results of sulfur analyses performed upon the vegetation growing on the CNF and Billings sites for the years 1975 and 1976, and 1976 and 1977, respectively. As can be seen from this figure, sulfur levels are mugh higher at Billings than they are on the Custer National Forest. Needles in their first year of growth are seen to have 900 ppm of sulfur in Billings, as opposed to 550 ppm for the comparable-aged foliage on the Custer National Forest. By the time the foliage is in its fifth year of growth, the levels of sulfur at Billings have risen to an average of 1,350 ppm, while the same-aged foliage has only 400 ppm of sulfur on the Custer National Forest. Reference to Appendix A, Figure A-42, which presents the sulfur levels recorded in 1976 and 1980 at the Billings site shows that these levels decreased between 1976 and 1980. The 1976 average for the older needles was

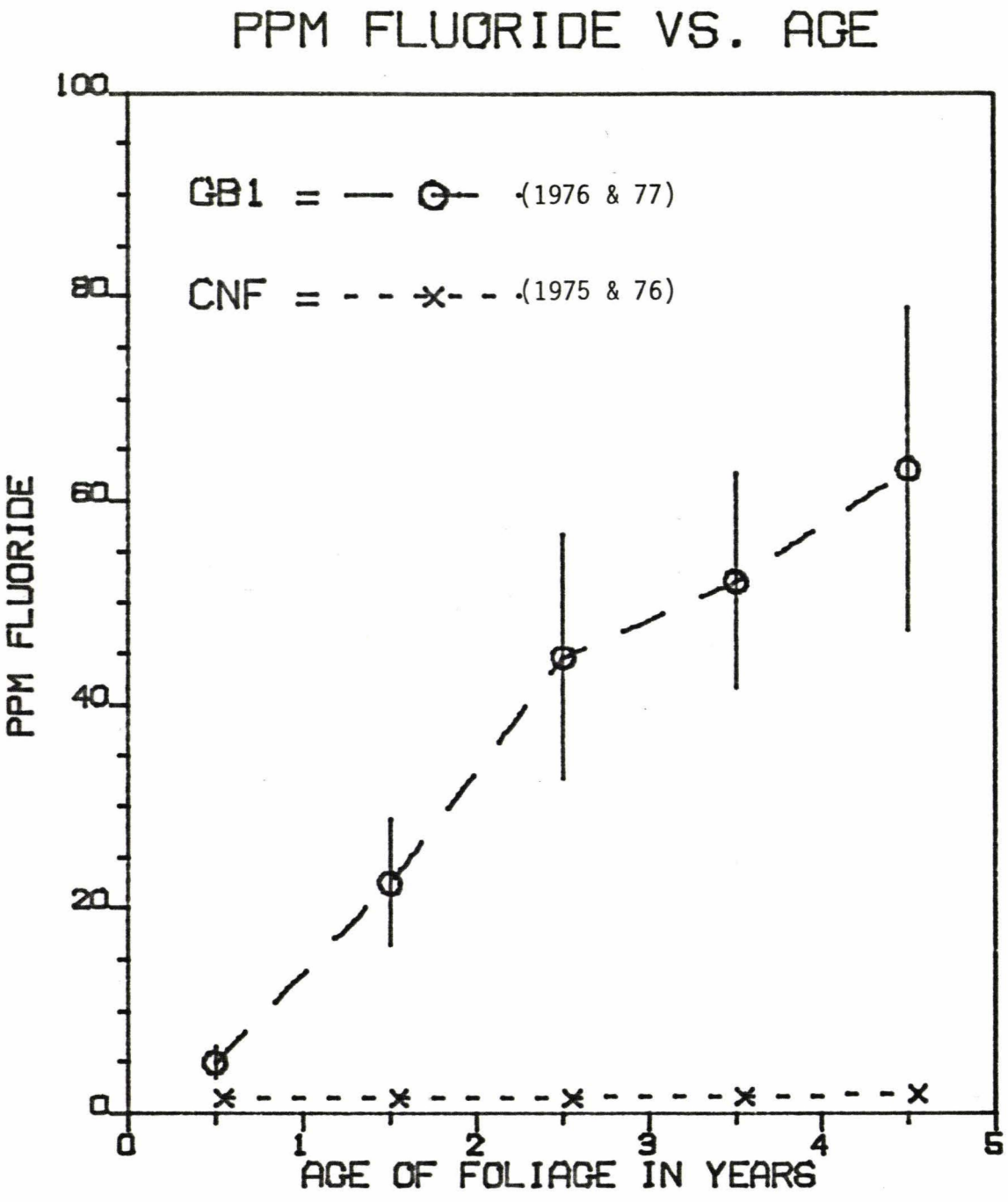

Figure 38. Ppm fluoride in ponderosa pine needles at all CNF sites (1975 and 1976 collections) and GB 1 (1976 and 1977 collections).

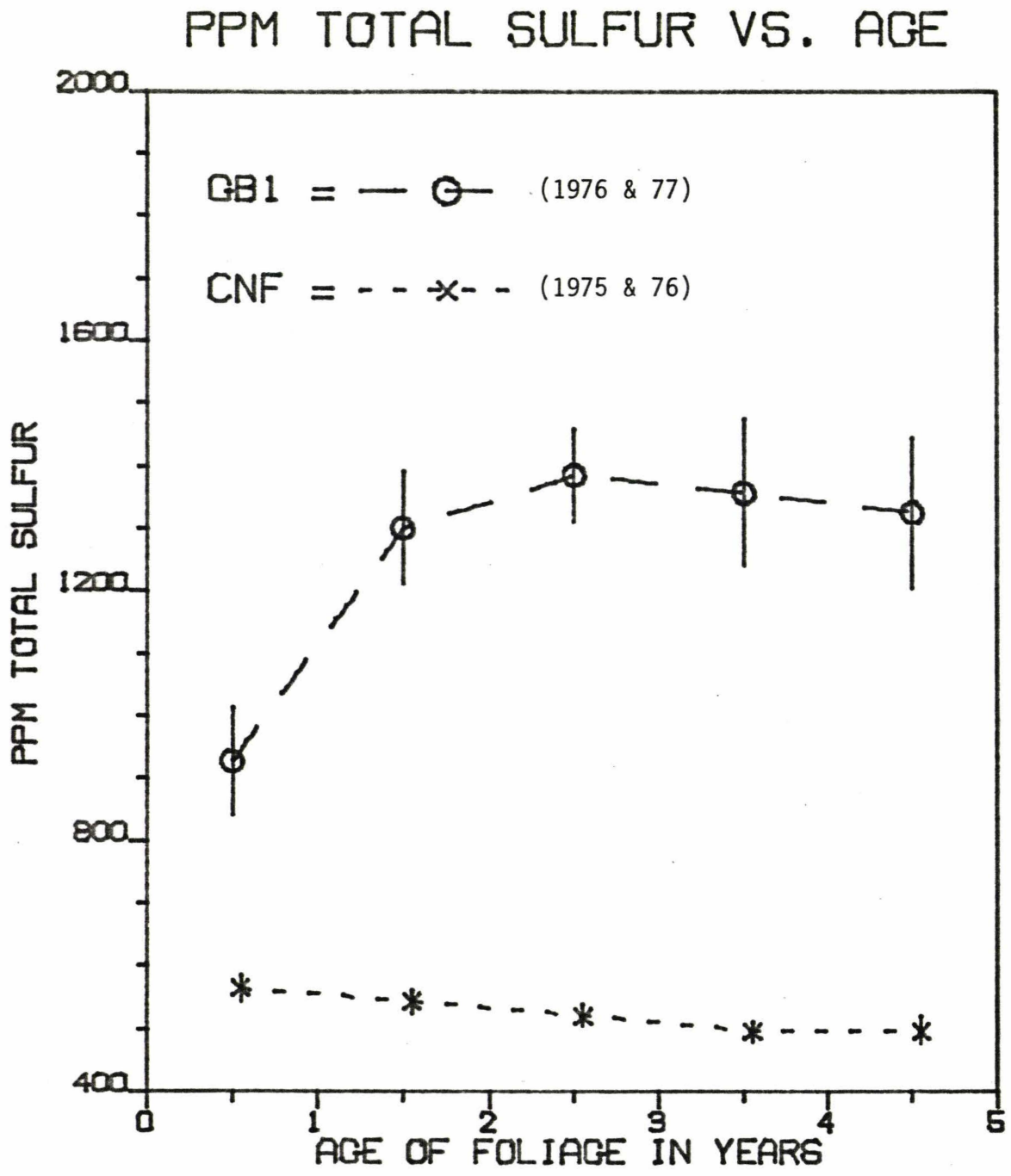

Figure 39. Ppm sulfur in ponderosa pine needles at all CNF sites (1975 and 1976 collections) and GB 1 (1976 and 1977 collections).

1,375 ppm, and in 1980 the average was 1,250 ppm. It can be concluded from this that the sulfur concentration in pine needles is an indicator of air pollution.

Figure 40 contrasts the levels of tip burn seen at Billings with those in the Custer National Forest. This figure demonstrates that there is more tip burn at Billings than was on the Custer National Forest in 1975 and 1976, although in 1980, the Custer National Forest had levels of tip burn that were only slightly lower than the values reported at Billings (Figure 4). From this it can be concluded that the percentage of needles with tip burn, in and of itself, is not sufficient to demonstrate the presence of air pollution.

The amount of needle surface that is damaged by tip burn, however, is larger at Billings than it is on the Custer National Forest, either in 1975 or 1980. This can be seen most readily in Figure 41, which shows the percentage of affected tissue that existed on the various years of foliage at the GB 1 site in 1976 and 1977 (the first two years there variables were quantified) and 1979 and 1980 (the latest two years of data available). It can be seen from this figure that approximately 1% of the total surface area of the first year needles and 25% of the surface area of needles in their fourth year of growth was necrotic due to the presence of tip burn. The average for all years of foliage is seen to be about 4% at the GB 1 site. This is contrasted to the levels on the Custer National Forest as were shown in Figure 5. In this figure, it is shown that the average amount of necrotic tissue due to tip burning for all ages of foliage was about 0.25% in 1975 and 2% in 1980. Reference to Appendix A, Figure A-343, which presents the levels of tip burn at Billings in 1976 and 1980 reveals no change in the average amount of tip burn damage between the two collections.

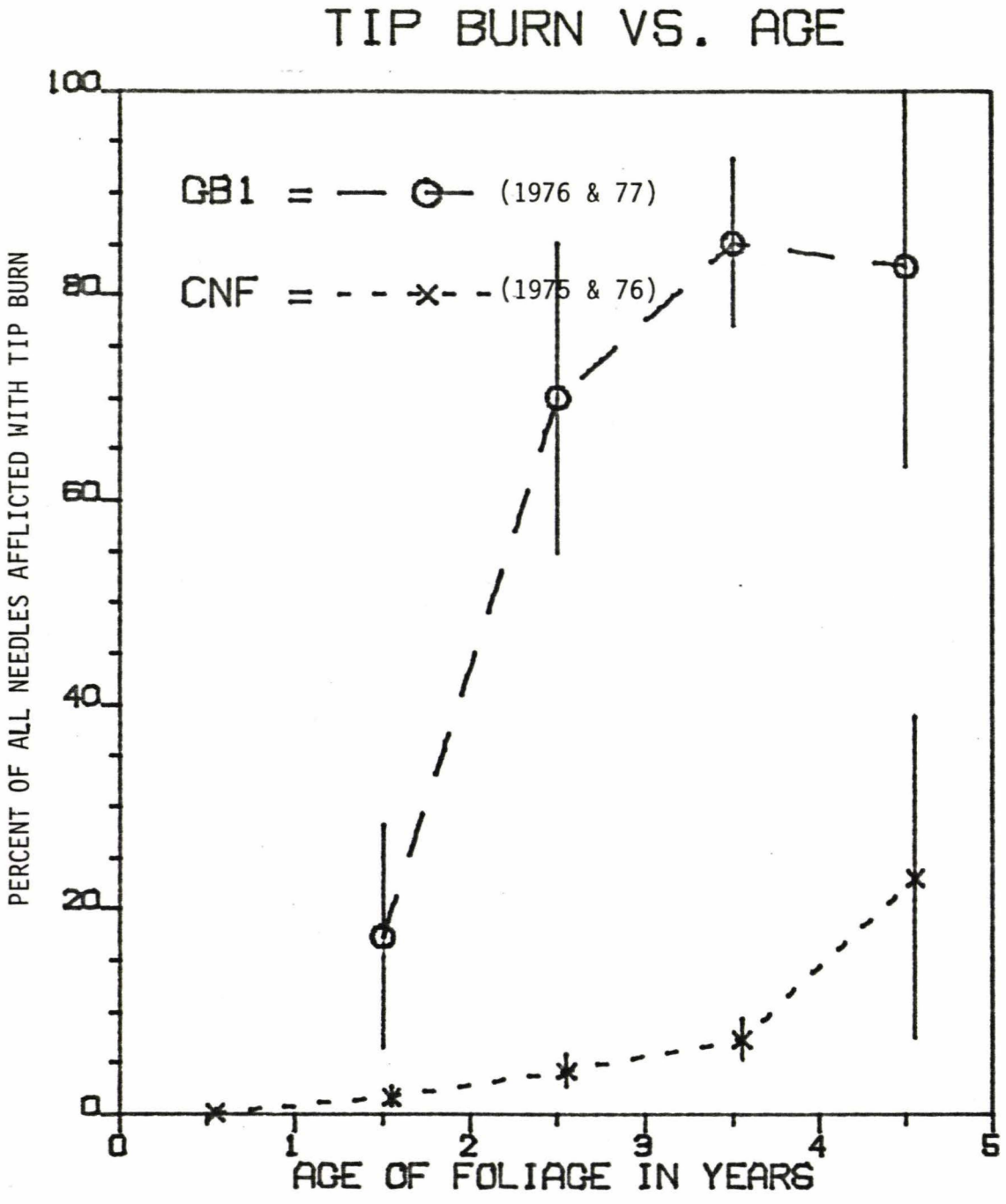

Figure 40. Percent of ponderosa pine needles afflicted with tip burn at all CNF sites (1975 and 1976 collections) and GB 1 (1976 and 1977 collections).

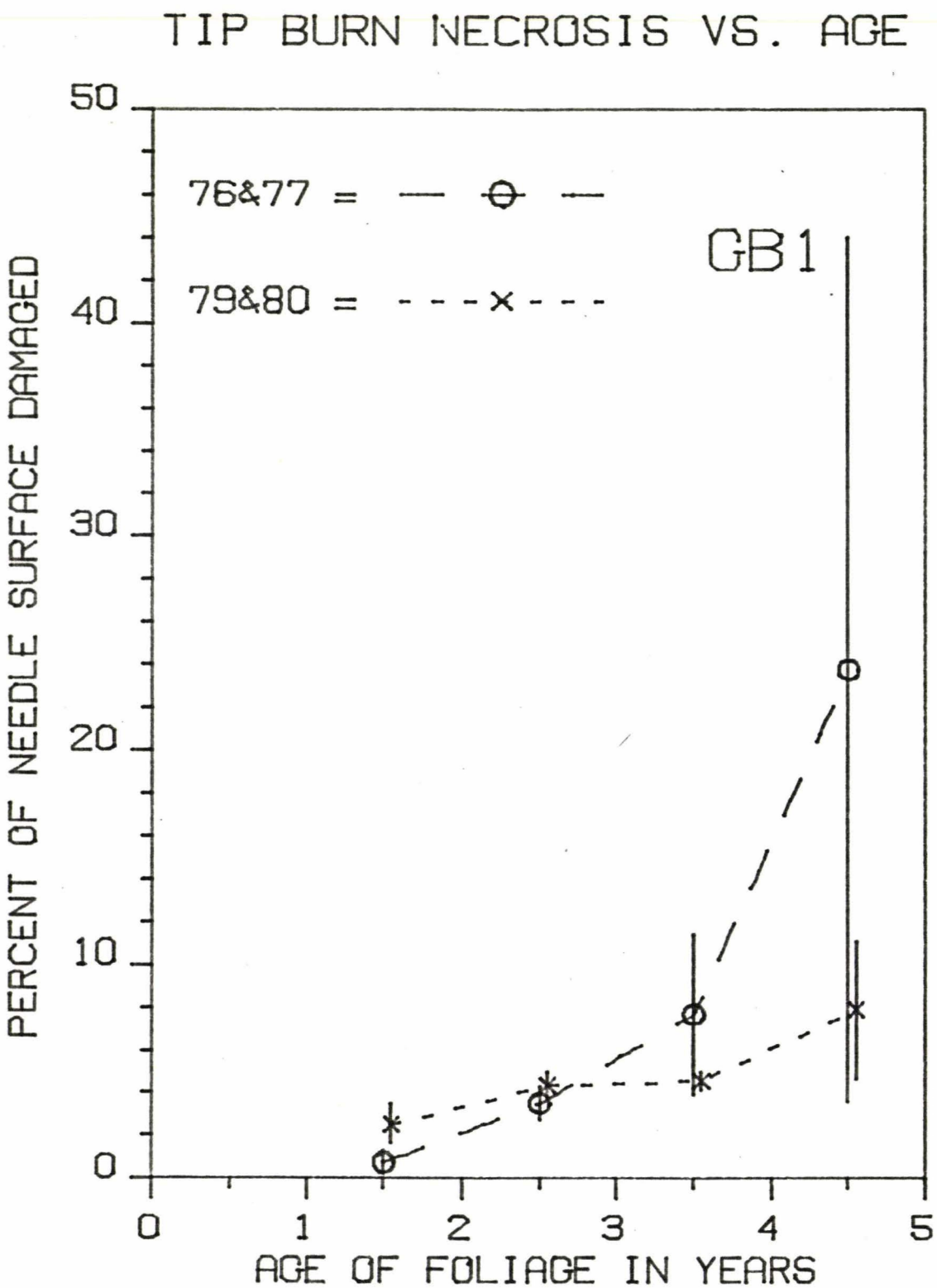

Figure 41. Percent of ponderosa pine needle surface damaged by tip burn at GB 1, 1976 and 1977 collections, 1979 and 1980 collections.

The situation with mottling is very much the same as that for tip burn. Figure 42 contrasts the levels of mottling seen in Billings in 1976 and 1977 with the levels seen in the Custer National Forest in 1975 and 1976. Although the levels of mottling are much higher than the levels in the Custer National Forest in 1975 and 1976, they are lower than the levels of mottling seen on the Custer National Forest in 1980 (Figure 7). From this we can conclude that the percentage of mottled needles, per se, is not an indication of pollution. Rather, as in the case of tip burned needles, the difference lies in the percentage of the needle surface that is affected by mottling.

Figure 43 shows the percent of needle surface affected by mottling at GB 1 for the years 1976 and 1977, as well as the years 1979 and 1980. It can be seen that the amount of needle damage varied from 5% to 25% of the total foliar surface. The comparable levels existing on the Custer National Forest in 1975 and 1980 were presented in Figure 8. It was shown in this figure that in 1975, the levels were less than 1%, and in 1980 the values ranged between 2% and 6%. The average levels of mottling damage at Billings fell from 30% in 1976 to 15% in 1980 (see Appendix Figure A-405).

Figure 44 contrasts the levels of basal scale and necrosis combined on the Custer National Forest with the levels at Billings. It can be seen from this figure that there was more basal pathology at Billings in 1976 and 1977 than there was at the CNF sites in 1975 and 1976. Since the 1980 levels of basal pathology on the Custer National Forest are the same as the 1975 and 1976 levels (Figure 10), while the frequency of occurrence of tip burn and mottling rose, it can be concluded that the percentage of needles with some form of basal damage is a better indication of pollution, in and of itself, than the percentage of needles with tip burn or mottling. Reference to Appendix Figure A-147 indicates that the average percentage of needles with

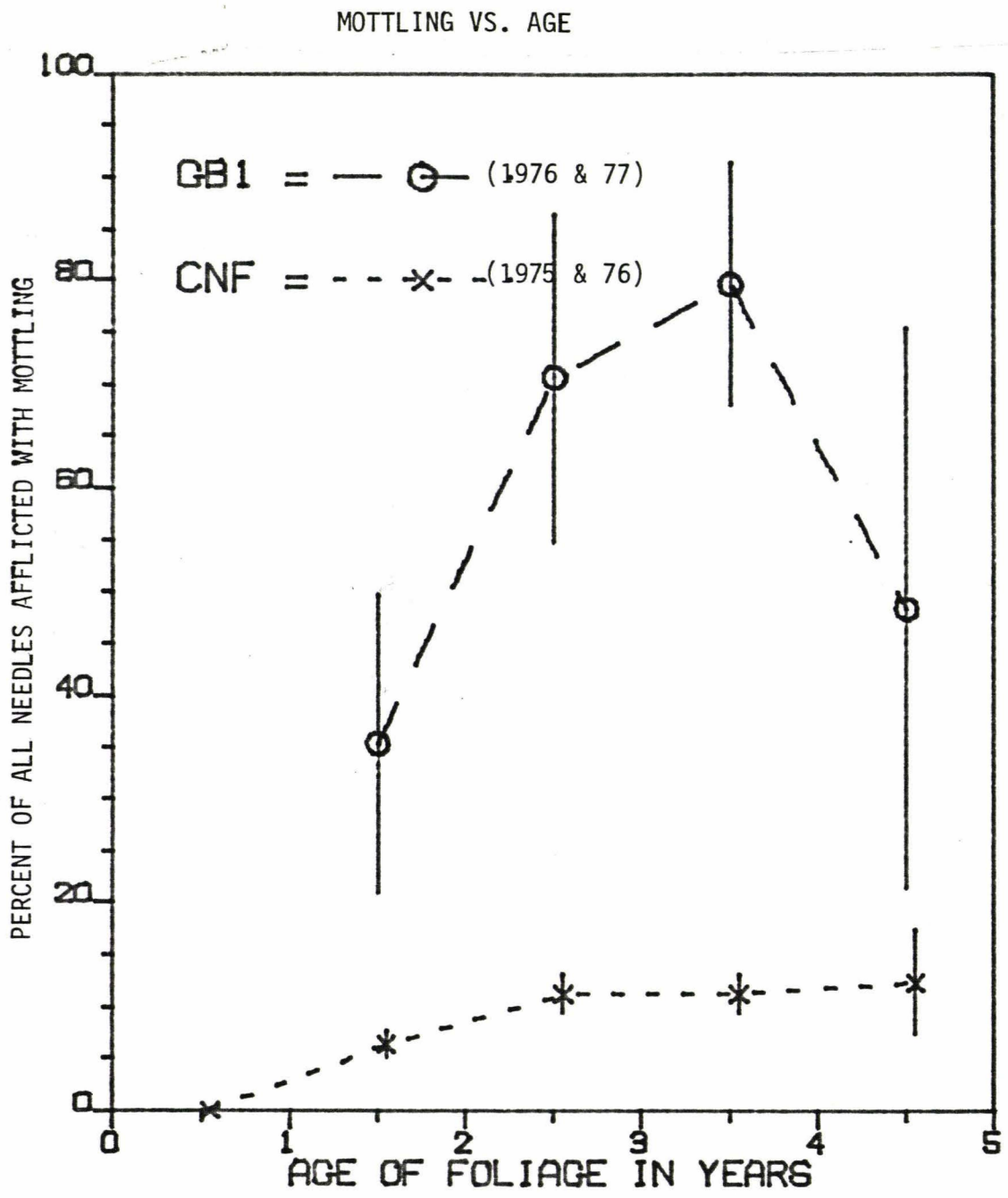

Figure 42. Percent of ponderosa pine needles afflicted with mottling at all CNF sites (1975 and 1976 collections) and GB 1 (1976 and 1977 collections).

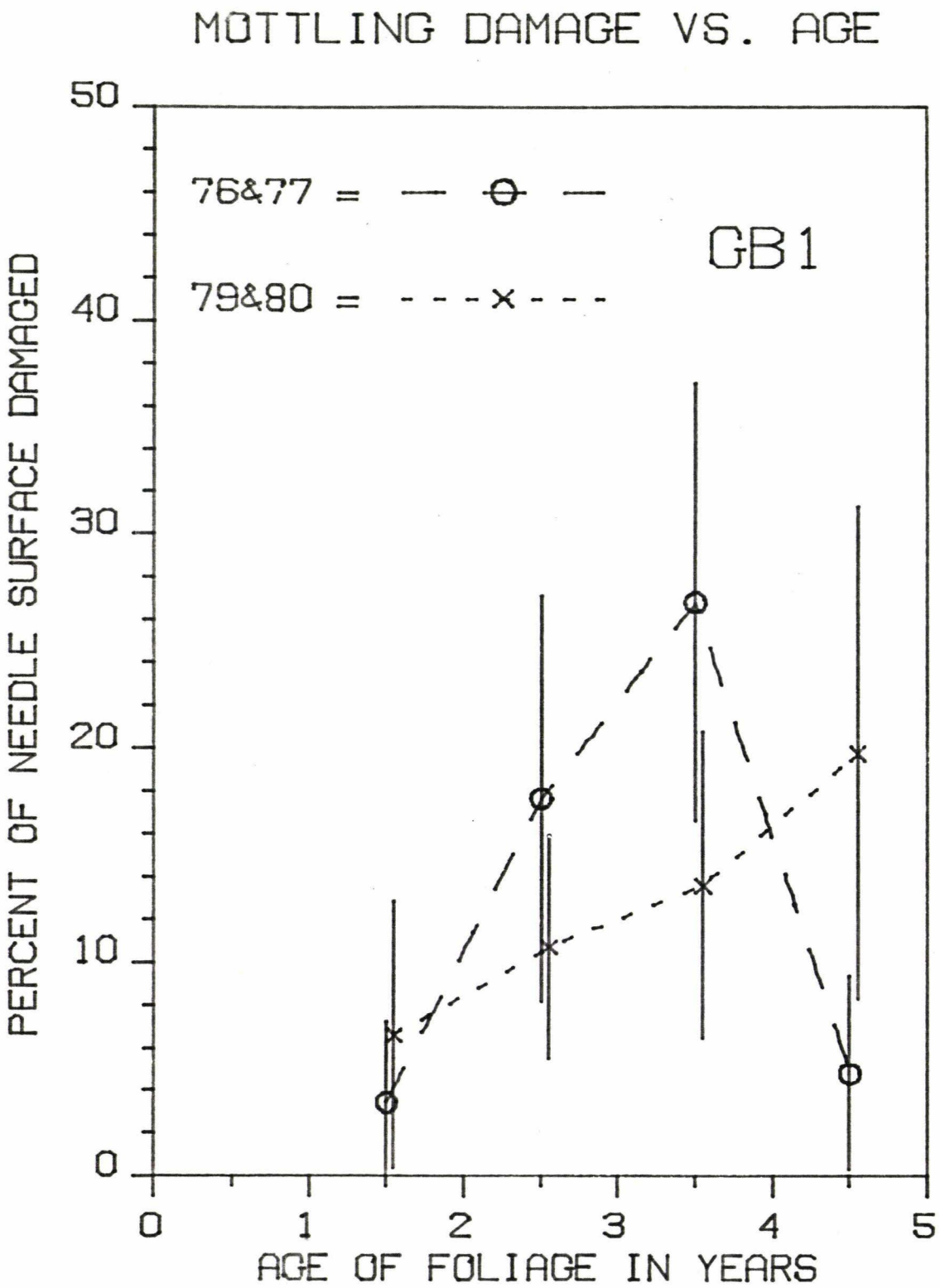

Figure 43. Percent of ponderosa pine needle surface damaged by mottling at GB 1, 1976 and 1977 collections, 1979 and 1980 collections.

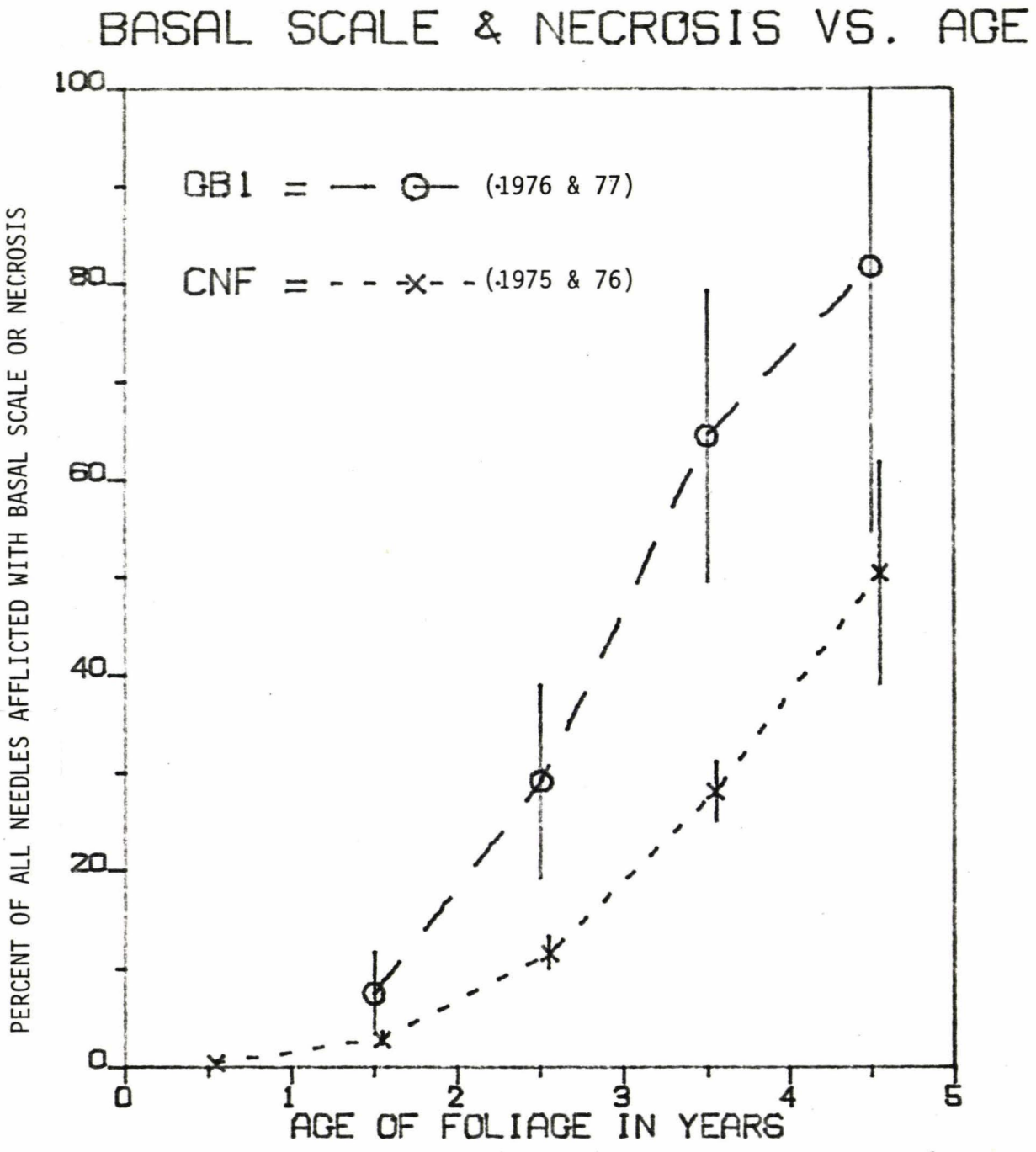

Figure 44. Percent of ponderosa pine needles afflicted with basal scale and/or necrosis at all CNF sites (1975 and 1976 collections) and GB 1 (1976 and 1977 collections).

with some form of basal damage fell at Billings from 43% in 1976 to 23% in 1980.

Figure 45 compares the levels of healthy needles at Billings in 1976 and 1977, and the Custer National Forest in 1975 and 1976. It can be seen from this figure that the levels of healthy needles at Billings are much lower than the levels of healthy needles on the Custer National Forest in 1975 and 1976, although they are very similar to the levels of healthy needles seen on the Custer National Forest in 1980 (Figure 16). It can be concluded from this that the percentage of healthy needles on a tree is not a good indicator of pollution. It is, rather, the amount of the total foliar surface area damaged that is the indicator of air pollution.

Figure 46 presents the amount of needle necrosis seen on GB 1 in the years 1976 and 1977, and 1979 and 1980. As shown, between 5% and 50% of the total foliar surface area of the needles growing on Sacrifice Bluff were damaged by a pathology of some kind. The overall levels of foliar damage fell from 25% in 1976 and 1977, to 15% in 1979 and 1980. Figure 18 displays the comparable data from the Custer National Forest in 1975 and 1980. This figure indicates that the levels of total needle necrosis were lower on the Custer National Forest, ranging between 1% and 15% of the total foliar surface area.

Turning now to Figure 47, the level of needle retention at Billings is contrasted with the retention data collection on the Custer National Forest in 1975 and 1976. It can be seen from this figure that the needle retention is reduced at Billings from the 1975 and 1976 levels on the Custer National Forest. These values are lower than the 1980 CNF levels as well. The differences are especially noticeable in the older needles.

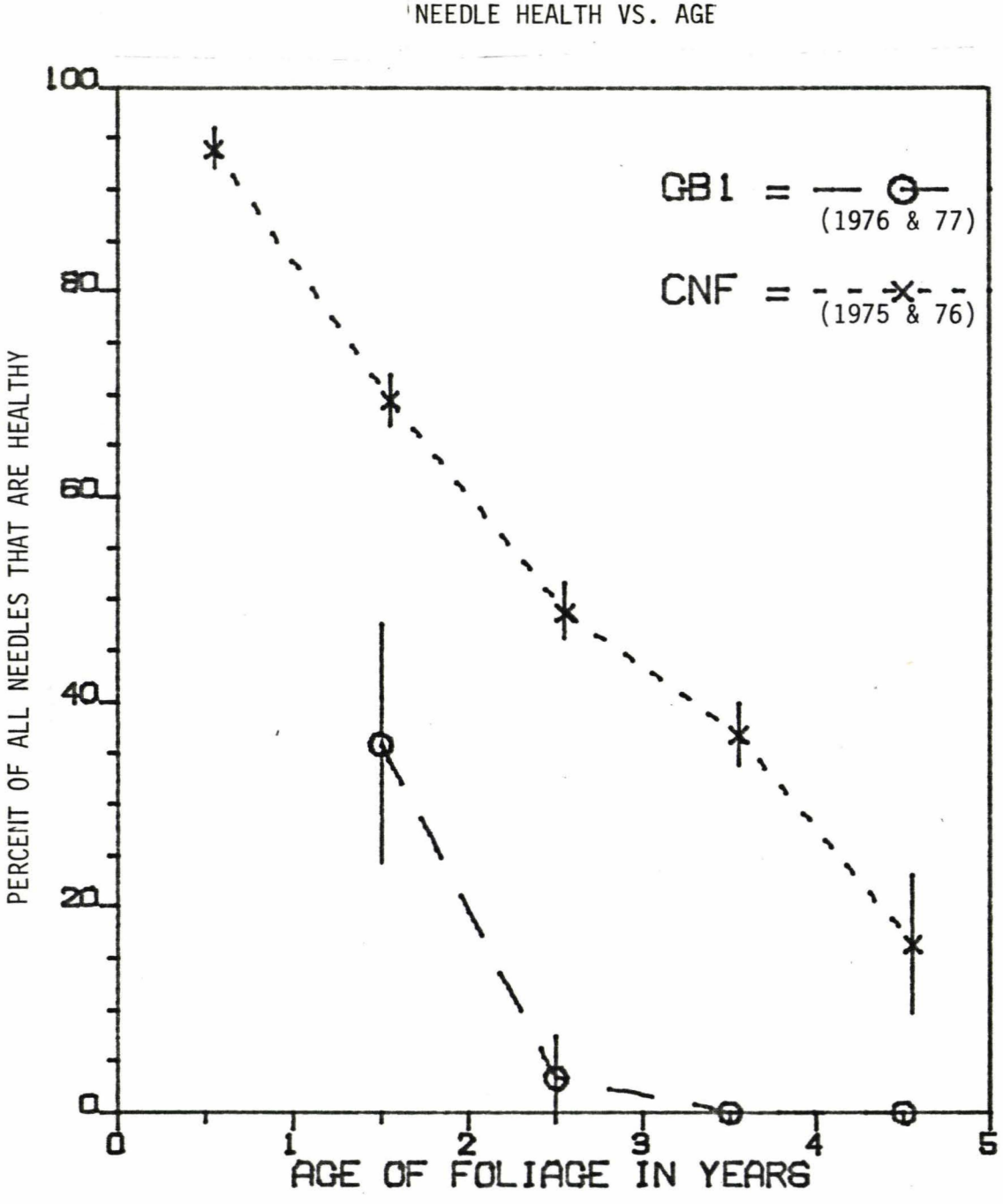

Figure 45. Percent of all ponderosa pine needles that are healthy at all CNF sites (1975 and 1976 collections) and GB 1 (1976 and 1977 collections).

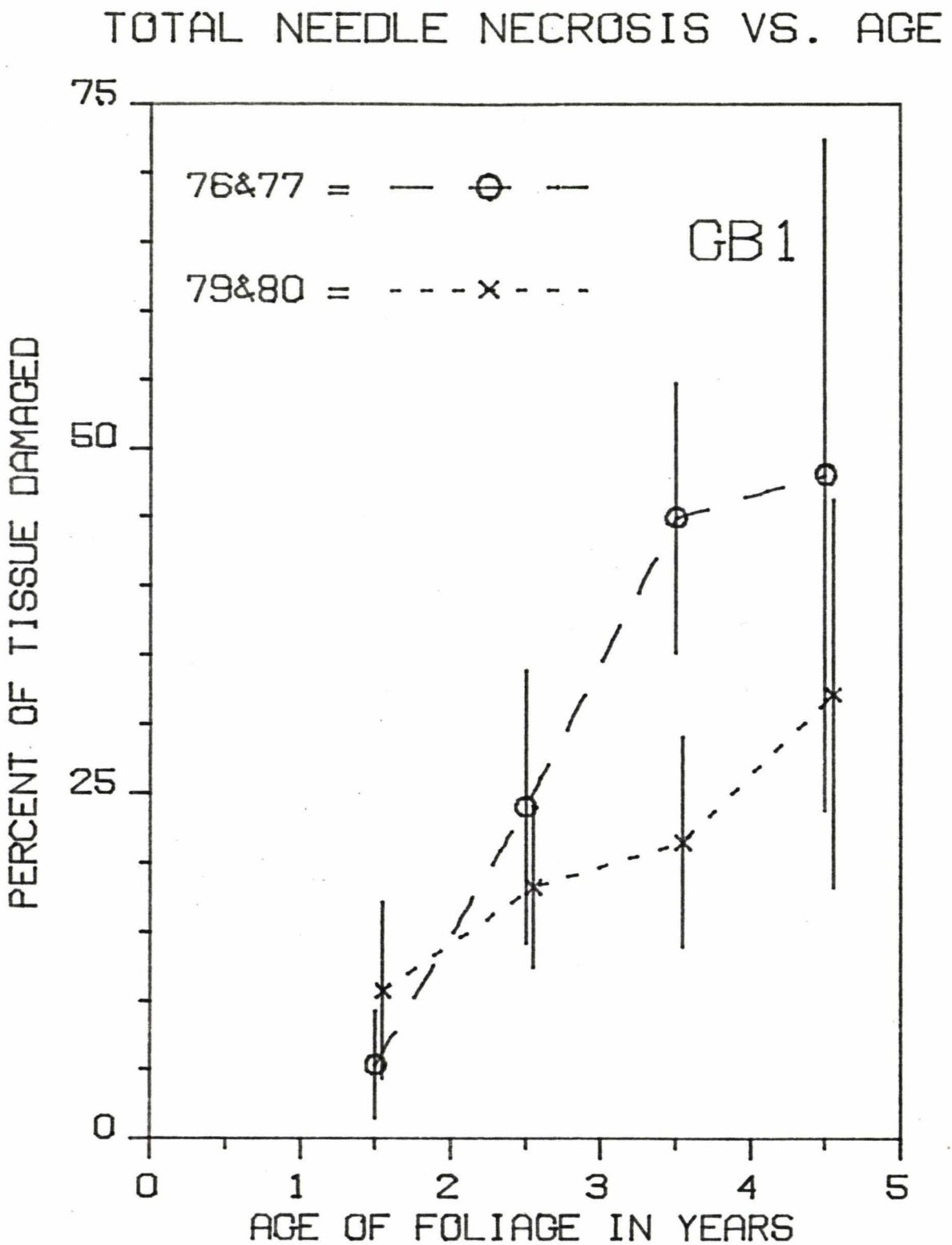

Figure 46. Percentage of ponderosa pine needle surface that is damaged by pathologies at GB 1, 1976 and 1977 collections, 1979 and 1980 collections.

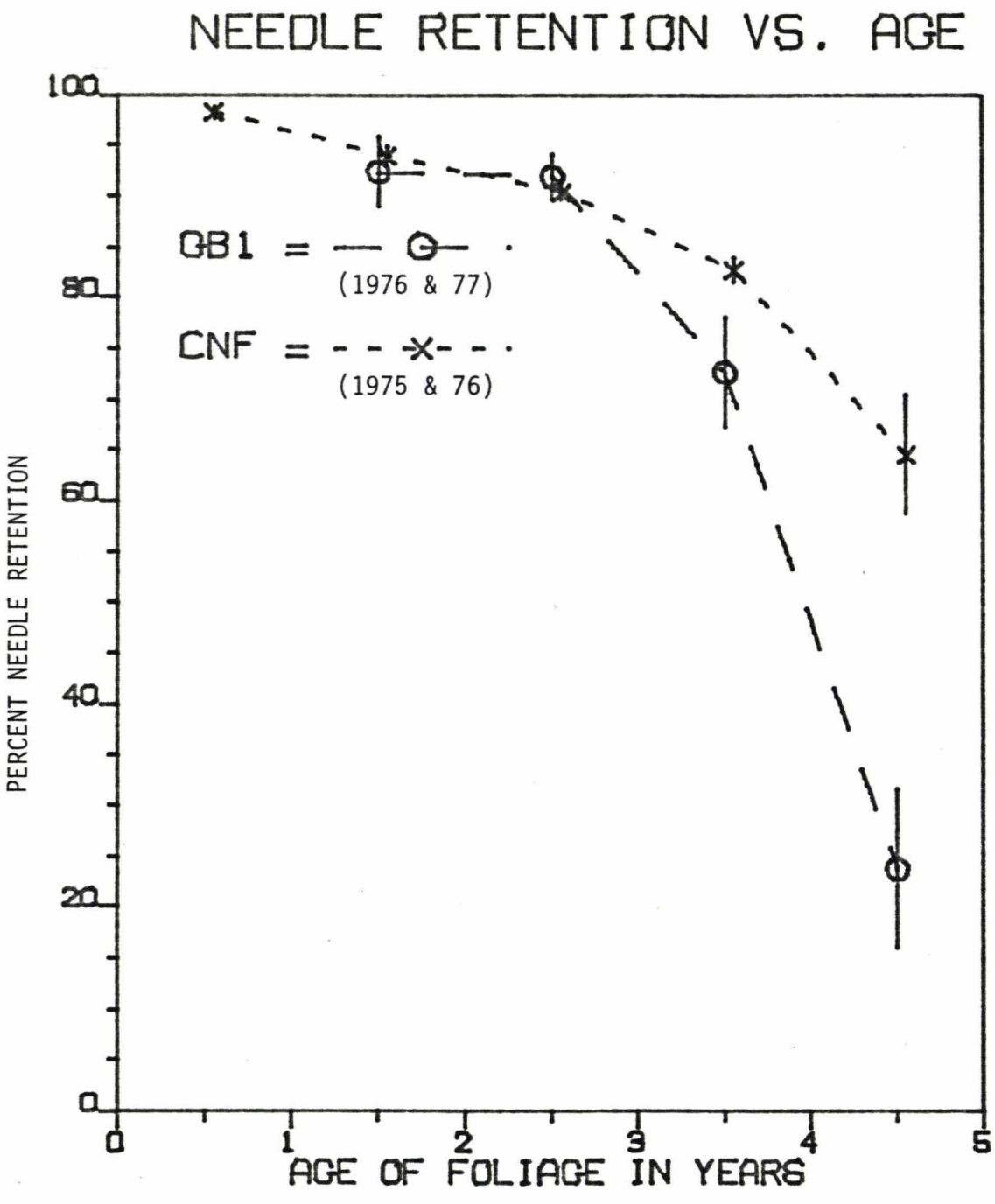

Figure 47. Percent of ponderosa pine needle retention at all CNF sites (1975 and 1976 collections) and GB 1 (1976 and 1977 collections).

Figures 48, 49, and 50 compare the average needle lengths, cross sectional areas, and dry weights, respectively, recorded at Billings and CNF sites in the years 1976 and 1977, and 1975 and 1976. It can be seen that there are no differences in any of these variables that would suggest the effect of pollution is present.

DISCUSSION AND CONCLUSIONS

The fluoride concentrations rose on the Custer National Forest by 1.64 ppm in 1980 over the corresponding levels in 1975. Although the sites within 25 km of Colstrip had higher average increases than those sites more distant than 25 km, there was no correlation between distance and fluoride concentration in foliage. This fact, coupled with the observation that insufficient fluoride is emitted in a year by Colstrip Units 1 and 2 to account for all of this added fluoride, indicates that Units 1 and 2 are not the sole source of fluoride.

The average sulfur concentration in pine foliage was 60 ppm higher in 1980 than it was in 1975. Although the Colstrip Units 1 and 2 do emit enough sulfur to account for this increase, once again the lack of any correlation between distance from Colstrip and sulfur concentrations in foliage casts doubt on the power plants being the sole source of the additional sulfur.

Without examining in greater detail the collections made on the Custer National Forest in 1976, 1977, 1978, and 1979, it is impossible to state when these increases began, and consequently, all that can be concluded at present is that the fluoride and sulfur concentrations in pine foliage have increased on the Custer National Forest for unknown reasons, although the power plants at Colstrip cannot be entirely eliminated as a possible cause.

In 1975, tip burn occurred on 3.8% of all needles, and 0.26% of the total foliar surface area was affected on the Custer National Forest. In 1980, 49%

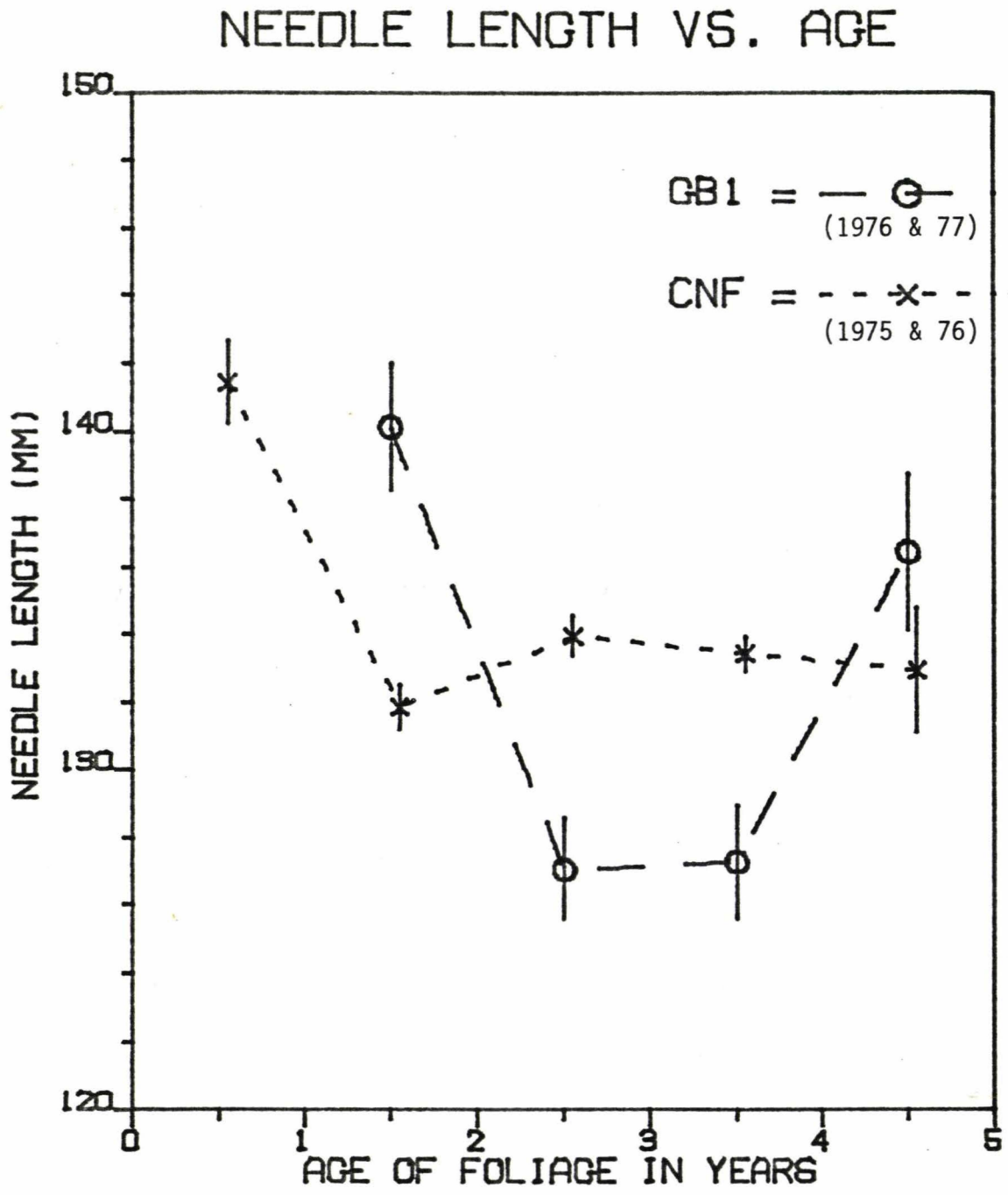

Figure 48. Average ponderosa pine needle length at all CNF sites (1975 and 1976 collections) and GB 1 (1976 and 1977 collections).

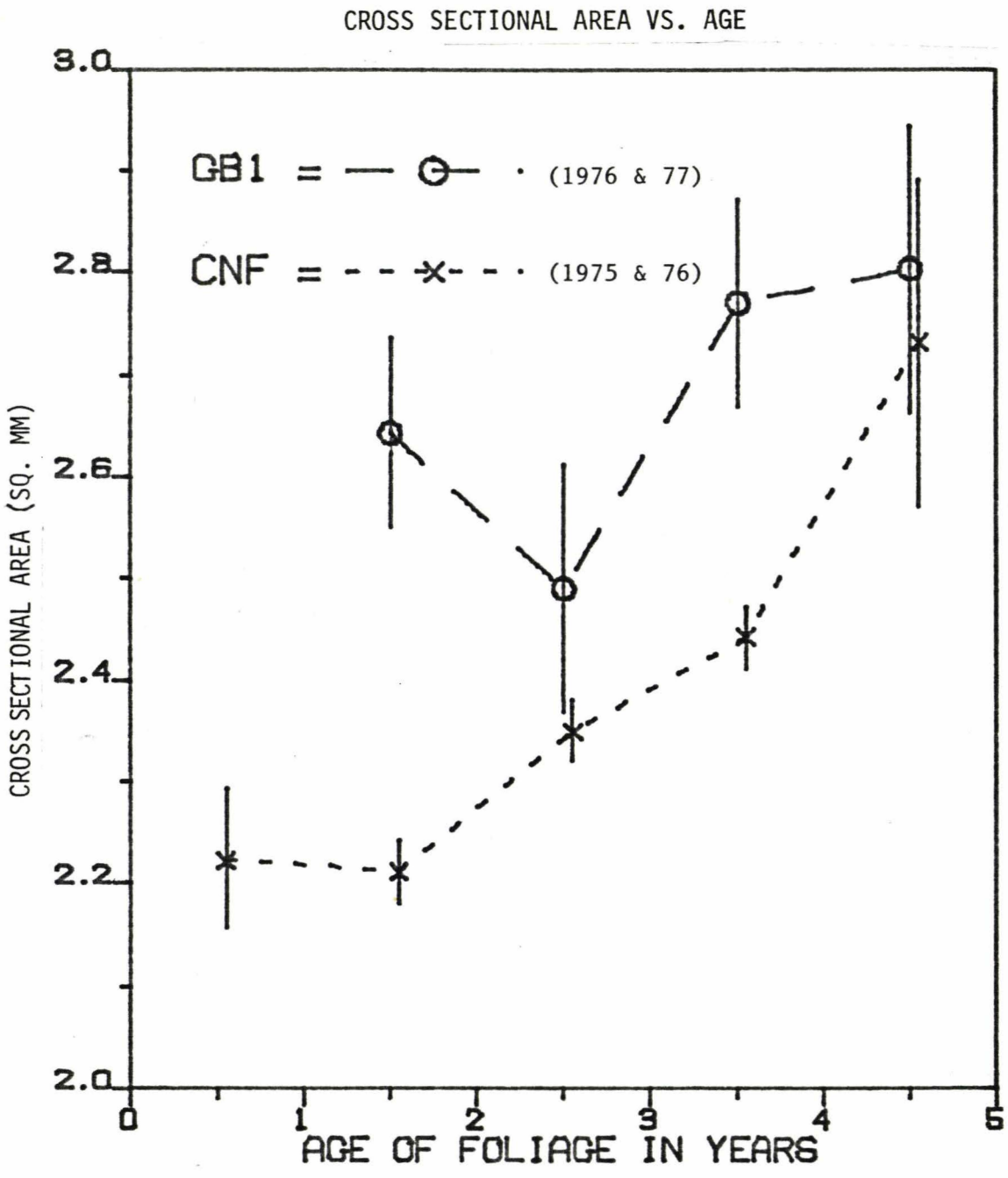

Figure 49. Average cross sectional area of ponderosa pine needle bundle at all CNF sites and GB 1.

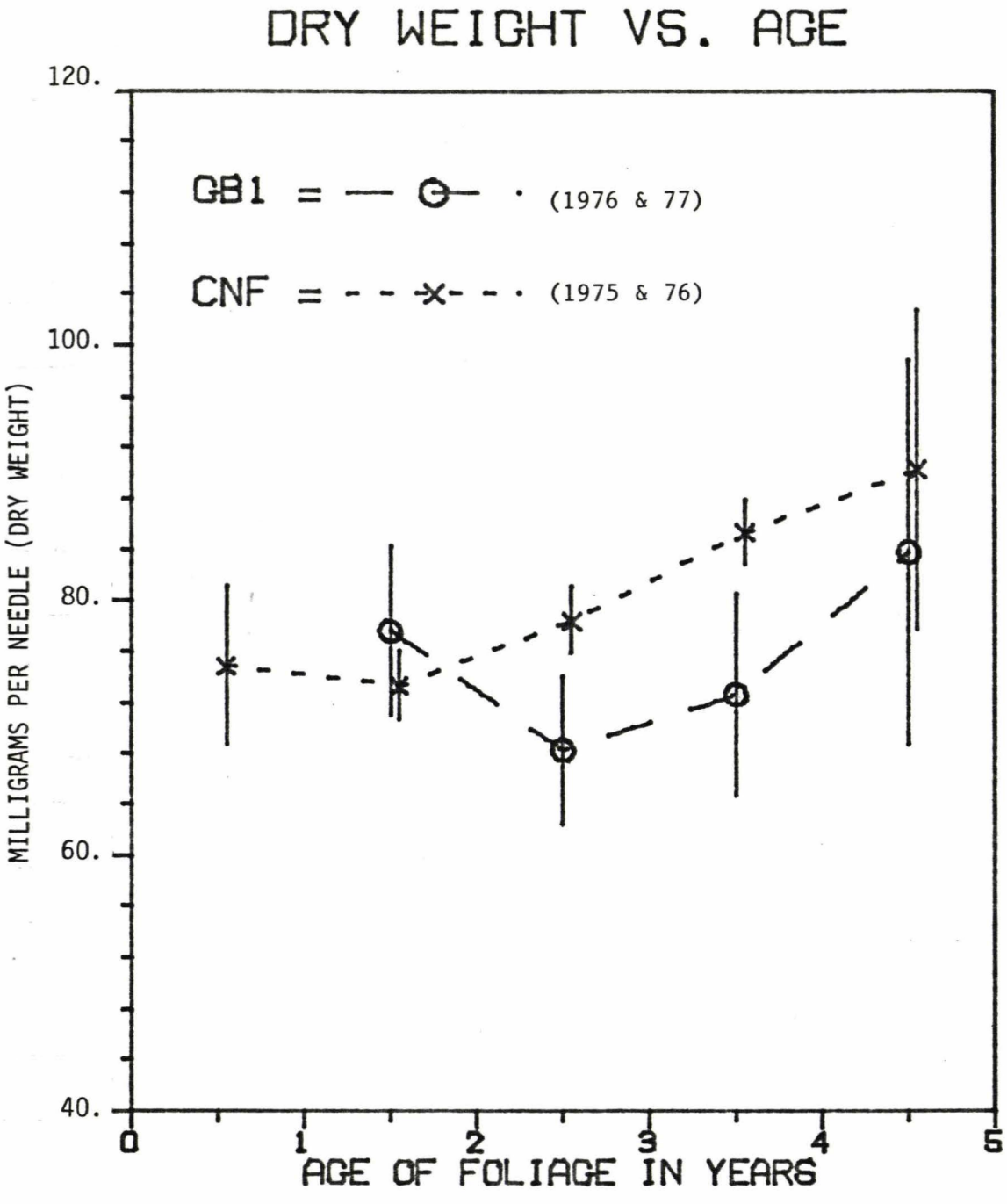

Figure 50. Average dry weight of one ponderosa pine needle at all CNF sites and GB 1.

of all needles were tip burned, and 1.2% of the total foliar surface area was affected. The increase in the number of tip burned needles with increasing age was seen to follow a first order differential equation. This implys that the process resulting in tip burn is a stochastic one with a constant probability of a non-tip burned needle becomming tip burned in any given year. This was the case for both the 1975 and 1980 collections, suggesting that the same mechanism was responsible for damaging needle tips in both 1975 and, albeit at an accelerated rate, 1980.

In 1975, mottling occurred on 6.5% of all needles and damaged 0.39% of the total foliar surface area on the Custer National Forest. In 1980, mottling appeared on 67.8% of all needles and damaged 3% of the total foliar surface area. The nature of the increase in mottling with increasing age changed between the 1975 and 1980 collections, however, suggesting a new cause of mottling was present in 1980. In 1975 the mottling primarily occurred on the first-year needles, whereas in 1980, needles were becoming mottled at a constant rate throughout their lifetime. Based on the data herein, it is impossible to determine the specific cause of the additional mottling, although it is apparent from the rate of mottling with increasing age that it is a non-age selective process and might well be associated with the increase in fluoride and sulfur levels. By examining the intervening years of collection, it will be possible to determine if the increases seen in 1980 are representative of an anomolous year or if these values have been rising steadily since 1976, the year that coal conversion began at Colstrip.

The levels of weevil damage were similar in 1975 and 1980 on the Custer National Forest. On the average, 10% of the needles had some form of weevil damage, and 2% of the total foliar surface area was damaged. There were no increases in the number of needles damaged by weevils or the amount of surface

area damaged by weevils after the first year of growth. This implys that the weevil are age selective agents and attack the younger needles to the exclusion of the older ones.

In 1975, miscellaneous pathologies occurred on 11.7% of the needles and damaged 2.2% of the total foliar surface area. In 1980, 42.4% of all needles had some form of miscellaneous damage, although the total amount of foliar damage remained near the 1975 levels, rising slightly to 2.5%.

The above pathologies combined to produce damage on 42% of all needles in 1975 and 93% in 1980. In 1975, 4.6% of the total foliar surface area was damaged, and in 1980, 8.6% of the total foliar surface area was damaged. If the weevil damage is subtracted from the total foliar surface area damaged, then 2.5% and 6.6% of the total foliar surface area were damaged in 1975 and 1980, respectively.

The frequency of occurrence of basal pathologies remained constant on the Custer National Forest in 1975 and 1980, averaging 11% and 8%, respectively. Unlike mottling in 1975 and weevil damage, which display decreased rates of damage as the needles age, and unlike mottling in 1980 and tip burn, which display constant rates of damage as the needles age, basal damage rates increase as the needles age. This can be explained in one of two ways, with perhaps the differences between the explanations being the chicken and egg question. As the fascicular sheaths loosen with age, access to the base of the needle by atmospheric pollutants, insects, etc. is facilitated, which could result in increased rates of basal damage. If, on the other hand, the loosening of the basal sheath is a consequence of increased basal damage, then the increased rates of basal damage seen as the needles age reflects an aging process where the needles maintain healthy bases until their third and fourth years when they begin to be affected.

Needle retention was slightly less in 1980 than it was in 1975 on the Custer National Forest. The differences were primarily in the younger needles, however, not in the older needles as would be expected if the increased loss was due to atmospheric pollution.

The study site located at Sacrifice Bluff had consistently higher foliar concentrations of fluoride, sulfur, basal dmage, and total foliar necrosis and lower levels of needle retention than on the Custer National Forest, either in 1975 or 1980.

The average concentrations of fluoride and sulfur in the 1976 and 1980 collections made at Billings were 32.7 ppm and 1,310 ppm, respectively. At Billings, 3.34% of the total foliar surface was damaged by tip burning, mottling damaged 20.5% of the total surface area, and miscellaneous pathologies damaged another 3.34% of the total surface area. These pathologies combined to damage 27.4% of the total foliar surface area. Basal pathologies were found on 38.4% of all needles, and needle retention average 83.5%.

Foliar concentrations of fluoride and sulfur, as well as the frequency of occurrence of basal damage and the percent of total foliar surface area damaged fell at the Billings site between 1976 and 1980. The fact that fluoride, sulfur, basal damage, and total necrosis rise and fall together suggest a common cause.

Based on the above discussion, it is concluded that the levels of fluoride, sulfur, basal damage, and needle retention can serve as indicators of pollution. The amount of foliar surface area that is damaged by mottling and tip burn can also serve as an indicator of polluiton, although the percentage of needles afflicted with tip burn and mottling is not. The average needle lengths, cross sectional areas, and dry weights at the Billings and CNF sites do not differ significantly, casting doubt on their value to indicate the presence of air pollution.

The frequency of occurrence of tip burn and mottling in 1975 can be described as negative bionomials with a characteristic k for each pathology.

As the mean probability of occurrence rises, the assumption of the pathologies being rare events breaks down and the negative binomial no longer fits the data. At this point, the data can only be described as the mean of randomly varying binomial distributions. As the mean proportion of a pathology continues to rise, the absence of the pathology begins to become a rare event and the negative binomial once again fits the data if it is expressed as the number of needles observed without the pathology. This changing shape of the distribution is strongly a consequence of the fact that the counts of the pathologies have an upper bound of 100 counts in 100 needles observed.

To extend the validity of the negative binomial, more needles could be sampled from a tree, although a better approach is to theoretically derive the distribution of the mean of a randomly varying binomial. The exact distribution of the frequency of occurrence of these pathologies is, however, of secondary importance as indicators of pollution. The primary variable is herein seen to be the total amount of foliar damage due to all pathologies (exclusive of weevil). This statistic is more readily transformed into a normally distributed one, as it is a sum of individual, independent observations (the amount of damage caused by each of the pathologies).

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